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Assessment of High Strength Steels for the Construction of Arctic Vessels and Structures - Phase 2

Final Report by: Det norske Veritas (Canada) Ltd.

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CANMET Scientific Authority: Dr. W. Tyson

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ASSESSMENT OF HIGH STRENGTH STEELS FOR THE CONSTRUCTION OF ARCTIC VESSELS AND STRUCTURES PHASE 2

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FINAL REPORT

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by

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TABLE OF CONTENTS

1. THE TWO TYPES OF EXTRA HIGH STRENGTH (EHS) STEELS
   - 1.1 Introduction
   - 1.2 Quenched and Tempered (QT) Steel
     - 1.2.1 General
     - 1.2.2 Chemical Composition
     - 1.2.3 Mechanical Properties
   - 1.3 Controlled Rolled Accelerated Cooled (CONRAC) Steels
     - 1.3.1 General
     - 1.3.2 Chemical Composition
     - 1.3.3 Mechanical Properties
2. DIFFERENCES FROM NORMALIZED STEELS, POTENTIAL PROBLEM AREAS
   - 2.1 Introduction
   - 2.2 QT Steels
     - 2.2.1 Effect of Thermal Treatment (Welding, PWHT) on Material Strength
       - 2.2.1.1 Soft Zones Along Welds
       - 2.2.1.2 PWHT, Effect on Base Material Strength
     - 2.2.2 Fracture Toughness and Defect Acceptance Criteria
     - 2.2.3 Fatigue Properties
     - 2.2.4 Hydrogen Induced Stress Corrosion Cracking (SCC) in Sea Water
   - 2.3 CONRAC Steels
3. APPLICATION OF EHS STEELS
   - 3.1 Workshop Procedures
     - 3.1.1 Gas Cutting
     - 3.1.2 Forming, Effects of Cold Deformation and Ageing
     - 3.1.3 Flame Straightening
     - 3.1.4 Industrial Experience with Fabricattion in EHS Steel
   - 3.2 Welding
     - 3.2.1 Risk of Hydrogen Induced Cold Cracking, Preheat Requirements
     - 3.2.2 HAZ Fracture Toughness
   - 3.3 Post Weld Heat Treatment (PWHT)
     - 3.3.1 General
     - 3.3.2 PWHT of QT Steel
     - 3.3.3 PWHT of CONRAC Steel

3.4 Experience with EHS Steels

3.4.1 Availability of High Strength Steels Suitable for Arctic and Sub-Arctic Service

3.4.2 Experience with Fabrication in EHS Steels

3.4.3 Service Experience

3.5 Technical Points Still Under Consideration

3.5.1 Fatigue

3.5.2 SCC in Seawater under Cathodic Protection

3.5.3 Welding Consumables/Weld Metal Properties

3.5.4 HAZ CTOD Fracture Toughness

4. ECONOMIC POTENTIAL

4.1 Main Advantages

4.2 Estimated Saving Potential

4.2.1 Substructures

4.2.2 Topside Structures

4.2.3 Single Structural Items

5. CONCLUSIONS

6. REFERENCES AND INFORMATION SOURCES ON EXTRA HIGH STRENGTH STEEL

(1.1) General Survey Articles

(1.2) QT STEEL

(1.3) CONRAC Steel

(1.4) Workshop Procedures

(1.5) Welding/Weldability/Consumables

(1.6) Fracture Toughness/Local Brittle Lanes

(2.) VERITEC Reports (Proprietary)

Executive Summary

An assessment of the techno-economic feasibility of using Extra High Strength (Re_{min} from 420 MPa to 500 MPa) steels for ships and offshore structures, particularly with respect to Arctic and Sub-Arctic conditions. The EHS-steels covered include the Controlled Rolled Accelerated Cooled (CONRAC) steels.

Based on the experience with such steels in offshore platform and icebreaker applications, a review of potential problem areas and experience summary from the applications are given. The experience with the fabrication of such steels is limited, but positive for both offshore platforms and icebreakers. The service experience is also very limited and of short duration.

Potential savings for offshore structures are of the order of 6 - 30 percent of weight, and up towards 50 percent saving (theoretically) of weld metal volume. Further, the avoidance of Post Weld Heat Treatment (PWHT) means potential savings of the order of US$ 125 per m weld.

The weldability and parent metal mechanical properties of the modern EHS steels (Quenched and Tempered (QT) and Thermo-Mechanically Controlled Process (TMCP)) are in general good and are at least comparable to the properties of normalized 350 MPa yield strength steels.

EHS steels that can meet the base metal Charpy impact and Crack Tip Opening Displacement (CTOD) toughness requirements at test temperatures expected for Arctic and Sub-Arctic service are commercially available. The selection of welding consumables that can consistently fulfil toughness and strength requirements is considered a crucial point for the application of these steels. The available consumables with the relevant properties exist, but not necessarily "off the shelf".

From the design point of view, more care and attention must be given to the fatigue properties. Techniques like grinding of weld toes and the use of improved shape of important elements by using castings or forgings may have to be considered.

1. THE TWO TYPES OF EXTRA HIGH STRENGTH (EHS) STRUCTURAL STEELS

1.1 Introduction

In principle the term EHS steels comprises steels with minimum specified yield strength (σ_y) ranging from 420 MPa to above 1000 MPa. However, for the present study dealing with easily weldable (low Pcm value) structural steels, only the yield strength range from 420 to 500 MPa will be considered.

The cost of manufacturing a heavy steel structure is to a first approximation directly related to the total weight of the steel. Reduction in steel weight will therefore have an approximately proportional effect on cost. Estimates of weight savings achievable by using steel of σ_y = 500 MPa in steel decks for fixed offshore platforms have indicated savings in the range 15 - 18% of the total weight. Thus, an increased use of EHS steel is believed to have a large economic potential.

In addition, weight reductions will for certain conditions be imperative due to operational requirements such as crane capacity, installation by lifting instead of launching, etc.

The use of EHS steel and therefore thinner material thicknesses also presents possibilities for important cost reductions during fabrication. The smaller amounts of weld deposit required for butt welds in thinner plate material is an obvious example. However, the possibility of reduced extent of preheating and post weld heat treatment (PWHT) also points to significant cost reductions.

So far the use of EHS steel in offshore and ship structures has been limited and there are relatively few projects where such steels have been used to any extent. The main reason for this is that in conventional welded structures no improvement in fatigue properties is obtained by using EHS steel instead of the common normalized high strength steels (HS, σ_y = 350 MPa). Furthermore, since the E-modulus of EHS steels is the same as for lower strength steels, it must be remembered that buckling problems may arise if the reduced stiffness of thinner EHS plates is not taken into consideration.

In the North Sea Area, a limit has provisionally (mainly due to lack of experience

experience) been set by oil companies such as Statoil, Norsk Hydro and Saga on a minimum specified yield strength of 500 MPa. This is also reflected in a recently published document from the Norwegian Petroleum Directorate (NPD): "Guidelines for Selection of Material and Fabrication of Steel Structures in Petroleum Activities". In this document it is stated that the use of steels with higher yield strength (than 500 MPa) must be considered for each individual case.

Also offshore steel specifications such as "The Engineering Equipment and Materials User Association: Steel specification for fixed offshore structures". EEMUA 150 limits the offshore steels to grades with minimum specified yield strength $\leq$ 450 MPa.

In the following therefore, emphasis has been put on weldable structural steels with minimum specified yield strength (Re_{min}) in the range of 420 - 500 MPa. The steels are either delivered in the thermo mechanically controlled processed (TMCP-steels) or the quenched and tempered (QT) condition.

There are today two main types of weldable structural EHS steels:

- Quenched and Tempered (QT) steels, and
- Controlled Rolled Accelerated Cooled (CONRAC) steels.

The latter type is often referred to as TMCP steel (Thermomechanical Control Process), or CONRAC steel. In the following the latter term will be used.

Below a brief presentation is given of these two classes of steels, with examples of typical chemical compositions and mechanical properties.

Section 4 assesses the techno-economic feasibility of using high strength steels for ships and offshore structures. The assessment was made with particular emphasis on Arctic and Subarctic applications.

1.2 Quenched and Tempered (QT) Steels

1.2.1 General

It has long been known that quenching and tempering produces a particularly favourable combination of strength and toughness. On the other hand, in older versions of QT steels the weldability was severely limited due to the content of alloying elements necessary to give sufficient hardenability.

In recent years, however, significant improvements of both alloying and quenching techniques have taken place. In particular the development of the more efficient roller quenching technique should be mentioned. This has made it possible to use much leaner steel chemistries in plate thicknesses up to 70 - 80 mm, with accompanying strong improvement of weldability.

This development has opened up for the possibility of a more widespread use of EHS QT steels, keeping in mind the limitations for fatigue loaded welded structures, and that due attention must be given to the possibility of buckling.

1.2.2 Chemical Composition

Important factors which are influenced by the detailed choice of steel composition are:

- Hardenability
- Max. HAZ hardness; as welded, and after post weld heat treatment (PWHT)
- HAZ CTOD fracture toughness
- Base material low temp. toughness
- Directionality of properties (amount and shape of non-metallic inclusions, in particular sulphides)

Strength properties (Re, Rm) are mainly influenced in a more indirect way, through the effect of steel chemistry on the response to heat treatment, and hence microstructure.

Some typical examples of compositions and carbon equivalents of modern structural QT steels are given in Table 1.1.

Table 1.1 Chemical Compositions and Carbon Equivalents of Three Modern Structural QT Steels

Element	Steel No. 1	Steel No. 2	Steel No. 3
C	0.11	0.11	0.09
Si	0.31	0.28	0.11
Mn	1.33	1.30	0.97
P	0.010	0.007	0.007
S	0.002	0.003	0.001
Al	0.045	0.055	0.021
Cu	0.12	0.01	0.15
Cr	0.15	0.02	0.17
Ni	0.32	0.50	2.40
Mo	0.04	0.11	0.42
V	0.06	0.03	0.03
Ti	0.011	0.001	0.007
N	0.007	0.003	0.003
CEIIW	0.41	0.31	0.55
Pcm	0.22	0.21	0.23

- Steel No. 1: St E 500 Rolled plate, t = 50 mm
- Steel No. 2: St E 500 Rolled plate, t = 50 mm
- Steel No. 3: HY 80 Mod. Forged plate, t = 120 mm

where the carbon equivalents are:

$$CEIIW = C + Mn/6 + (Cr + Mo = V)/5 + (Cu + Ni)/15$$

$$PCM = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$$

The low values of C and Pcḿ, and also the low contents of impurity elements (P, S, and N) are noted.

1.2.3 Mechanical Properties

The specified and actual mechanical properties of the steels in Table 1.1 are given in Table 1.2.

Table 1.2 Specified and Actual Mechanical Properties of the Three QT Steels in Table 1.1

	Steel No. 1		Steel No. 2		Steel No. 3	
	Spec.	Actual	Spec.	Actual	Spec.	Actual
Yield strength Re, MPa	500	529 X	500	587 X	460	566
Tensile strength Rm, MPa	-	628	-	647	-	635
Elongation A5, %	16	23	16	22	18	27
Red. of area Z, %	-	75	-	75	55	77
Charpy V transv. - 40°C, mean, J	47	158	47	186	50	223

x: Lower yield strength, ReL

1.3 Controlled Rolled Accelerated Cooled (CONRAC) Steels

1.3.1 General

In recent years a further development of the controlled rolling technology has been actively pursued, notably by Japanese steel manufacturers. The aim has been to develop competitively priced structural steels in thicknesses up to 100 mm or more,

with higher yield strength, improved fracture toughness in base metal and HAZ, improved weldability, and no HAZ hardness problems.

This might seem a formidable undertaking, but the development has successfully led to commercial steels being available which fit the above description well. These are the controlled rolled accelerated cooled (CONRAC) steels.

The various steelmaking companies have developed somewhat different production routes for this class of steel, and given them their own name. Examples are:

- CLC (Continuous On-line Control), Nippon Steel Corp.
- OLAC (On-line Accelerated Cooling) Nippon Kokan
- MACS (Multipurpose Accelerated Cooling System) Kawasaki Steel
- DAC (Dynamic Accelerated Cooling), Sumitomo Metal Industries

Steels of this kind possess excellent combinations of strength, toughness and weldability, which would make them strong contenders for structural applications in ships and offshore structures. In particular the high toughness at low temperatures makes these steels attractive from the point of view of arctic applications.

The min. specified yield strength for these materials is typically in the range 360 - 460 MPa.

Part of the key to the favourable combination of properties is that the CONRAC steels get a significant contribution to strength from the accelerated cooling which follows the controlled rolling. This makes it possible to use a leaner steel chemistry to attain a given strength level, thereby considerably improving weldability as compared to normalized grades of corresponding strength.

The high plate toughness of CONRAC steels is primarily achieved by the controlled rolling, usually finished near the Ar_3 temperature. However, close control of impurity elements such as N, O, P, S and H, as well as micro-alloying elements, also contributes to a high impact toughness, particularly in the HAZ.

Another feature of CONRAC steels is the uniform hardness distribution through the plate thickness. This is explained by the controlled rolling giving a finer austenite grain size at the surface than in the centre region of the plate. The hardenability is therefore greatest near the centre where the cooling rate is slowest, giving a tendency for hardening effects between the surface and centre to cancel. This results in the observed flat through thickness hardness curves.

The accelerated cooling starts just after finish rolling in the lower austenite range, and normally continues down to about 400°C. At this temperature the phase transformation is virtually completed and a stable microstructure is attained which essentially consists of a fine grained ferrite + pearlite/bainite mixture.

In welding the max. HAZ hardness is noticeably lower than in normalized steels of comparable strength, in agreement with the lower Pcm (or CEIIW) values.

1.3.2 Chemical Composition

The chemical composition of two typical CONRAC steels produced by two different steel producers is shown in Table 1.3. Steels No. 4 and No. 5 represent 50 mm and 30 mm plate material respectively. For both steels Re min = 420 MPa.

The general similiarity with regard to low content of main alloying elements and low Pcm values is noted, along with some differences in the microalloying additions (Ti, Nb, Al).

1.3.3 Mechanical Properties

The mechanical properties of Steel No. 4 and Steel No. 5 are shown in Table 1.4.

Table 1.3 Chemical Composition and Carbon Equivalents of Two Typical CONRAC Steels of Re min = 420 MPa

Element	Steel No. 4	Steel No. 5
C	0.08	0.04
Si	0.32	0.19
Mn	1.57	1.44
P	0.008	0.011
S	0.001	0.003
Cu	0.26	0.24
Ni	0.45	0.41
Ti	0.004	0.014
Nb	0.008	0.025
Al	0.046	0.034
N	0.0035	-
CEIIW	0.39	0.32
Pcm	0.19	0.14

Table 1.4 Mechanical Properties of the Two CONRAC Steels in Table 1.3

	Steel No. 4	Steel No. 5
Yield strength Re, MPa	484	450
Tensile strength Rm. MPa	574	559
Elongation A5, %	37	-
Charpy V transv. - 60°C, mean. J	342	274

The high impact toughness at low temperature is noted.

2. DIFFERENCES FROM NORMALIZED STEELS, POTENTIAL PROBLEM AREAS

2.1 Introduction

By far the greatest part of existing fabrication and in service experience for steel structures is from the use of the common normal strength and high strength (HS) steel grades. These are steels typically in the yield strength range 240 -360 MPa and with a normalized ferrite-pearlite microstructure.

When considering the use of EHS steel types, it must be realized that such steels have a different heat treatment and hence microstructure, to some extent a different chemical composition, and a higher yield strength. It is therefore clearly of importance to evaluate what the basic differences are between these steels and the normalized HS steels which form the basis for existing material, design and fabrication specifications.

2.2 QT Steels

In the following some points where EHS QT steels may behave differently from HS normalized steels are briefly discussed.

2.2.1 Effect of Thermal Treatment (Welding, PWHT) on Material Strength

The strength of a QT steel plate of given chemical composition is primarily determined by the temperature at which it has been tempered subsequent to the quenching operation. The higher the tempering temperature, the lower is the resulting strength of the material.

It is inherent in this situation that if a QT steel at some later stage is heated to temperatures in the same range or higher than the tempering temperature used during plate production, a reduction of strength will take place.

For structural QT steels the two most common situations when such heating may

occur are:

- Welding
- Post Weld Heat Treatment (PWHT)

2.2.1.1 Soft Zones Along Welds

During welding, at some short distance away from the fusion line, the heat from the welding process will expose the plate material to temperatures from ~ 650°C - ~ 750°C. These temperatures span the range from incipient overtempering to some slight transformation (note the short "soaking times" involved in normal weld thermal cycles) and represents the zone where local softening of the material may occur.

Veritec has recently studied the effect of softened HAZ zones on the strength of welds in QT steels of σ_y = 500 MPa. This was done by tensile testing of thin (2 - 3 mm thick) flat test bars taken out across welds. Different weld heat inputs and preheats were used, giving a range of weld cooling times ($\Delta t_{8/5}$). The plate thickness was 25 mm.

In these experiments, soft zone fractures occurred only at weld cooling times $\Delta t_{8/5} \geq$ 19 seconds. This corresponds to an arc energy of 3.6 kJ/mm at a preheat temperature of 20°C. For the test specimens which fractured in the soft zone (weld cooling times $\Delta t_{8/5}$ from 19 to about 60 seconds), only moderate reductions of the ultimate tensile strength ($\leq$ 7%) were observed.

The thin, transverse weld tensile specimens employed in the investigation, clearly represent a "worst case" situation. For full size multipass welds the situation regarding soft zones will be much improved because of the added constraint in a thicker specimen.

Furthermore, welding conditions giving weld cooling times as high as ~ 20 seconds are likely to be advised against due to the likelihood of reduced HAZ toughness resulting from such welding conditions. (See also Section 3.2.2).

In view of the above, it is considered unlikely that soft zones from welding will cause problems in practice for steels of σ_y = 500 MPa, at least for plates above 15 mm thickness and with requirements for HAZ toughness.

2.2.1.2 PWHT, Effect on Base Material Strength

The thermal cycle associated with PWHT may cause a permanent drop in strength if the temperature has been sufficiently high. This is a well known fact for QT-steel, and steel manufacturers routinely recommend PWHT temperatures which are not to be exceeded in order to safeguard against any significant drop in strength.

As a rule of thumb a QT-steel can be post weld heat treated under yard conditions at a temperature 40°C lower than its tempering temperature without loss of strength. This is in agreement with recent work at Veritec. Thus, for instance, by specifying a minimum tempering temperature of 620°C, ample safety against a permanent drop in strength during PWHT at 580°C will be ensured.

2.2.2 Fracture Toughness and Defect Acceptance Criteria

For structural steels within the range from normalized high strength steels (σ_y = 350 MPa) to QT steel (σ_y = 500 MPa) the toughness requirement in terms of critical CTOD is proportional to the yield stress for a given defect acceptance level. Correspondingly, for a given toughness the size of acceptable defects is approximately inversely proportional to the yield stress.

Hence, the toughness requirements (or the defect acceptance criteria) for an EHS QT steel will in general be more stringent as compared with a normalized high strength steel if both steels are utilized to the same degree with respect to their yield strength. However, even in the coarse grained HAZ which is usually the most critical region, high minimum fracture toughness levels can be ensured by restricting weld heat input (weld cooling times) to below a critical value. Once this high minimum toughness level is attained, the requirements for the repair of fabrication defects, as specified for normalized HS Steel, will be met.

The critical maximum heat input above which HAZ embrittlement starts to occur varies with steel chemistry. It should be noted that the same situation exists for normalized steel, and that the critical maximum heat inputs are in the same range for the two kinds of steel.

From a productivity point of view it is clearly of importance to select a steel with a high critical maximum heat input. This therefore constitutes an important point to be checked during the basic qualification/selection of materials. In Veritec's opinion the method best suited for this type of work is the CTOD Bead In Groove testing.

2.2.3 Fatigue Properties

The higher stress level in an EHS QT steel structure, compared with the case when normalized high strength steel is used, may have a negative effect on the fatigue life of the structure. This is so because the fatigue strength of a welded construction does not usually increase with the yield strength of the material. However, fatigue strength is to a large extent determined by local design, and proper design can improve fatigue performance of a welded structure considerably.

A literature survey of fatigue data covering the last 6 years of issues of relevant publications was made in May 1987, but for the type of QT steel considered the result was meager. In particular, for the most relevant environmental conditions of sea water corrosion with cathodic protection, experimental data applicable to QT steels appear to be lacking. This is also the case for fatigue crack growth data in the HAZ; all literature data consider base metal only.

However, available fatigue test data do not indicate that the fatigue performance of EHS QT steels is significantly different from that of normalized high strength steels, a view which is also reflected in present offshore fatigue design codes.

Recent test results (both QT and normalized steels) have indicated that sea water environment with cathodic protection may have a detrimental effect compared

with air environment on the fatigue strength of welded joints. This is contrary to the assumption implemented in present rules. However, this negative effect has been demonstrated also on normalized high strength steels, and no conclusion can be drawn that the performance of EHS QT steels should be worse in this respect.

2.2.4 Hydrogen Induced Stress Corrosion Cracking (SCC) in Sea Water

Structural steels exposed to sea water may be susceptible to stress corrosion cracking (SCC) when subjected to tensile stresses. It is well established that SCC is caused by embrittlement of the steel as a result of hydrogen pick-up, and that hard areas such as weld HAZ's are generally most susceptible.

The rate of hydrogen discharge on the steel surface is governed by the exposure conditions, and more specifically by the electrochemical potential of the steel. Cathodic protection is a key factor in this context, since the hydrogen discharge rate increases with decreasing (more negative) polarization potentials.

The stress corrosion cracking (SCC) resistance of cathodically protected structural steels in sea water, has traditionally been connected to the strength of the steel. In practice, hardness measurements of base material and weld zones have been used for assessing the SCC resistance. A maximum hardness level of 325 HV5 has normally been specified. It has, however, been argued that this level is too stringent and that a hardness level of maximum 400 HV5 in the weld zone may be acceptable with respect to SCC in normalized structural steels for plain sea water.

As for normalized steels, the welding of EHS QT steels may lead to hardness levels as high as 400 HV5 unless post weld heat treatment (PWHT) is applied. Furthermore, the high strength of QT steel has the potential of introducing higher tensile stresses and thereby giving rather high stress intensity factors in any (weld) defects.

The practical experience with respect to the SCC resistance for submerged steel structures and also relevant laboratory test data applicable for design is scarce for

EHS QT steel. More work should therefore be done to establish reliable criteria in this field.

2.3 CONRAC Steels

The CONRAC steels possess a favourable combination of strength, weldability (low Pcm values) and toughness at low temperatures.

Even so there has been a certain hesitation in the market to use this promising type of steel.

This situation, it is felt, is mainly due to the fact that there still remains some incompletely answered questions relating to the applications of these materials. This is not surprising since they are newcomers to the family of sructural steels and limited service experience is available.

Aspects where CONRAC steels are/may be different from normalized steels are:

- Weld Metal Cracking

  Due to the excellent weldability of CONRAC steel, heavy plates may be welded virtually without preheating. Since the resulting thermal cycles give less time for hydrogen diffusion, this may increase the risk of hydrogen cracking in the weld metal. What impact will this have on the selection of welding consumables?

- Heat Affected Zone (HAZ) Fracture Toughness

  It is well known that the common normalized C-Mn microalloyed structural steels have a tendency to develop local brittle zones in the HAZ during fabrication. Do CONRAC steels have the same tendency, and if so, to what extent?

- Directionality of Properties

Controlled rolling of steel plate is known to produce anisotropy in the material, that is properties which can vary considerably with the direction of testing. Controlled rolling constitutes an essential part of the processing route also for CONRAC steels and effects of anisotropy are known to occur. What is the significance of such effects and what can be done to avoid them?

- Softened Zones Along Welds

When EHS steels are welded, zones adjacent to the welds are heated to high temperatures and some loss of strength can occur locally. This is also the case for EHS CONRAC steels, and more data are needed. (See also Section 2.2.1.1 for QT steels).

- Several Varieties of CONRAC Steels

CONRAC steels are made by somewhat different processing routes by the various major steel producers. They are therefore less uniform and less well defined as a group than the normalized grades. This may give some uncertainty about what one is actually buying.

- More Data is Required

So far most of the work on CONRAC steels has been done by the steel manufacturers themselves. There appears to be a need in the market for more neutral, non-producer-generated data for the CONRAC steels, including comparisons with modern normalized HS steels.

3. APPLICATION OF EHS STEELS

3.1 Workshop Procedures

3.1.1 Gas Cutting

In general, low alloy QT steels are quite well suited to gas cutting. With the deliberately increased hardenability of QT-steel, however, and in particular for heavier thicknesses, it might be anticipated that gas cutting could lead to more pronounced hardened zones with an increased risk of cracking. This has also occasionally be observed in practice, but only for grades of $\sigma_y \geq 700$ MPa, and not, to our knowledge, for the $\sigma_y = 420 - 500$ MPa grades evaluated here.

In recent work at Veritec the effect of plate temperature, plate thickness, and surface condition during gas cutting, on the appearance, cracking tendency, and hardness of gas cut surfaces of three QT steels with yield strength $\sigma_y = 500$ MPa have been studied.

After gas cutting the cut surfaces were extensively examined by MPI and metallography with regard to possible defects. In no case, however, regardless of plate thickness, plate temperature when cutting, or degree of corroded surface used in the experiments, was any indication of cracking detected.

It is considered an important observation that all three steels tested were capable of being gas cut under conditions clearly more unfavourable than what is common in ordinary workshop practice, without showing any tendency to cracking.

It seems therefore that gas cutting of the modern low P_{cm}-value QT-steels ($\sigma_y = 500$ MPa) in thickness at least up to 50 mm, will not cause any cracking problems under ordinary workshop conditions.

3.1.2 Forming, Effects of Cold Deformation and Ageing

During fabrication, weldable structural steels are frequently given their shape by forming operations involving cold deformation. This holds also for QT steels of the type under consideration.

Cold deformation brings about work hardening of the material; it becomes stronger but at the same time loses some of its original ductility.

Different types of structural steels show basically similiar responses to cold deformation. However, the quantitative effects differ depending on the strength level and type of microstructure of the material.

Depending on the chemical composition of the material, and in particular the contents of interstitial nitrogen and carbon, cold forming of steel may also lead to effects of strain ageing.

Veritec has recently conducted an experimental study of the effects of cold deformation and ageing on the mechanical properties of three QT steels (σ_y = 500 MPa). Plate thicknesses were 25 and 50 mm.

It was found that such QT steels have a good ability to preserve ductility and impact toughness after deformation and ageing. For instance, after a standard strain ageing treatment (5% def., 1 h 250°C) the examined steels had a Charpy impact toughness at - 40°C of $\geq$ 70 J for 50 mm plate and $\geq$ 190 J for 25 mm plate. This is comparable to values for normalized steel.

The common cold forming operations such as recommended by steel manufacturers can safely be used for this type of steel without any subsequent heat treatment at least for plate thickness up to 25 mm, and presumably for all thicknesses $\leq$ 60 mm.

As compared to normalized steels the higher strength of QT steels leads to

higher forces being required during forming operations, and stronger spring back effects. It is essential that these effects are considered and accounted for when forming operations are planned.

3.1.3 Flame Straightening

During flame straightening a narrow zone of the material is locally heated in general by an oxygen acetylene torch. Maximum temperatures are often claimed to be in the range 500 - 700°C. Due to the cold material adjacent to the heated zone thermal expanison is prevented and the heated zone becomes permanently upset. During cooling thermal contraction leads to further shortening of the heated material, and stresses are set up which, when the process is properly conducted, give rise to the desired change of shape, straightening or curving as the case may be.

In order for this technique to give the desired result attention should be given to the following:

- The local heating must be applied on that side of the material where, through upsetting and subsequent shrinkage, a shortening is to be provoked.

- The steel must be heated to a temperature where it has a low strength and is therefore readily deformed (upset). Usually, a peak temperature in the range 600 - 700°C is aimed for. It should be emphasized, however, that during practical use of the method, the measurement of the actual peak temperature for comparison with a specified target temperature is not easily made. Most often therefore, under ordinary workshop conditions, the peak temperature is not measured but is estimated visually by the operator, and the straightening operation is to a large extent dependent on the knowledge and cunning of experienced personnel.

- The heating should be rapid, so that as little heat as possible is conducted away from the local area or zone to be heated.

- The limitation of the peak temperature is set not only to protect the material against unwanted effects but also to limit the size of the heated zone, and thereby ensuring an adequate straightening effect. For instance, for a given heating source, heating a steel to 900°C takes about twice as long time as heating it to 600°C. Therefore, in the former case much more heat diffuses into adjacent material, the heated zone becomes too large, and the straightening effect may be largely lost.

The flame straightening technique has been used both for normalized structural steel and for QT steel at least up to a strength of Re $\geq$ 700 MPa for many years. Although seemingly somewhat crude and not easily checked against procedure requirements in its practical form, it is not known to be a cause of problems such as generating defects or other initiation points for cracking.

Reported Work on Flame Straightening of QT Steels

From the open literature five references (1.4.2 - 1.4.6) have been found which, at least in pair, deal with the flame straightening of QT-steel. The main results in the papers, which are in good agreement, can be summarized as follows:

- Most of the work reported for QT steels is for yield strength levels of $\geq$ 690 MPa (1.4.2, 1.4.3, 1.4.4, 1.4.6). Reference (1.4.4) also includes work on QT steels of the Re $\geq$ 500 MPa class.

- A maximum temperature of $\leq$ 700°C is consistently recommended (1.4.2, 1.4.3, 1.4.4, 1.4.5, 1.4.6).

- Depending on the details of the heating procedure, changes in the microstructure were observed in the range 0.5 - 2 mm under the surface (1.4.5, 1.4.3).

- Charpy V-notch impact testing (test bars extracted 1 mm under heated surface) did not reveal any significant difference from unheated material.

The tensile strength was also found to be largely unaffected (1.4.3). These results were found from maximum temperatures of 735°C for Charpy testing and 800°C for tensile testing.

The work referenced above indicates that flame straightening of QT steel can be carried out without detrimental effects on mechancial properties.

It seems clear, however, that undesirable effects may occur if the work is not carried our in a proper way. In particular impairment of material properties may take place if a too high temperature is inadvertently used (2.4.4).

Reported Work on Flame Straightening of TMCP Steels

As with the QT steels TMCP steels may be less tolerant to flame straightening operations than normalized steels. However, very little independent work has been found that report extensive with flame straightening of TCMP steels. The reports that have been reviewed is therefore primarily technical reports from steel works. Two such reports (1.3.5, 1.3.6), one from Sumitomo (DAC steel and one from Nippon Steel Corporation (CLC steel), both indicate that flame straightening can be performed using a maximum flame straightening temperature of 900°C followed by water quenching with no significant deterioration of impact toughness (- 40°C or - 60°C) or strength.

Based on the above the following comments regarding use of flame straightening on EHS steels can be made:

1) In properly conducted flame straightening operations no significant deterioration of mechnical properties take place in EHS steel up to Re_{min} = 500 MPa.

2) However, since both strength and toughness fall off quite steeply once a certain relatively high level of heat input is exceeded, some form of heat control is still recommended.

3) Monitoring of the surface temperature during flame straightening operations by using a well calibrated optical pyrometer is a possible practical way of checking during the execution of the work.

4) Whenever feasible for practical/economical reasons the use of mechanized equipmennt should be considered. Such mechanised procedures, run in to produce a desired thermal cycle much improves the reproductivity of the method.

5) As guidelines for maximum heat input during flame straightening of QT steel (Re_{min} 420 - 500 MPa) the following is proposed:

   - The peak temperature shall not exceed 850°C,

   - The depth of the HAZ visible in a macro-section shall not exceed 2 mm.

6) For TMCP steels in general the recommendations from the steel mill with respect to application of flame straightening must be adhered to. However, it appears that most TMCP steel can be flame straightened using maximum temperature of 900°C followed by water quenching without suffering significant deterioration of the Charpy V impact toughness or strength.

3.1.4 Industrial Experience with Fabrication in EHS Steel

The type of steel may influence the operations which we here include in the term workshop procedures. These workshop procedures cover cold forming heat treatment/PWHT, gas cutting, milling and grinding flame straightening, etc.

In Table 3.1 we have summarized the answers received from the seven different yards regarding their fabrication experience with EHS steels.

Table 3.1 Experience Among Seven Different Yards Regarding Use of Cold Forming, Flame Straightening, PWHT/Heat Treatment (Gas) Cutting, Milling and Grinding During Fabrication in EHS Steels

Company	Type of construction	Steel	Thickness range (mm)	Experience			
				Cold forming	Flame straightening	PWHT/ Heat treatment	Cutting, milling grinding
1	Equipment module Primary deck structure	BS 4360 55FM 55FMZ (RQT 501) (OX 602)	< 75	Problems with capacity of mill, work subcontr.	Has been performed without any problems	No heat treatment or PWHT have been carried out	Not reported
2	Beams, Primary deck structure	BS 4360 55FM (RQT 501)	15-25	Not performed	Not reported	- Not performed	AC/OX cutting and grinding has been performed without problems
3	Critical elements of primary deck structure	WELDOX 500	50-60	No experience	Restrictions on fl. str. can cause problems with fit up	PWHT can be performed keeping the holding temperature, Th Th<Ttemp-30°C	Not reported
4	Process module	BS 4360 55FMZ	20-60	Not reported	Not reported	Not applied?	Not reported
5	Ship, Icebreaker	OX 602	8-50	No problems	Induction heating, only on thin plates 8-10 mm	Not reported	No problems reported
6	L,T,I,U and box-profile beams for offshore	BS 4360 55FZM (OX 602)	35	No experience	Not reported	Only limited experience from WPQT. No problems reported	No special problems with QT steels
7	Deck and end sections for module	BS 4360 55FZM (OX 602)	40-60	No experience	Not reported	Not performed	Somewhat higher wear on milling tools, grinding discs and on saw blades.

According to Table 3.1 cold forming of EHS steels does not normally lead to special problems except that due to the higher steel strength the capacity of the equipment for cold forming of heavy section thicknesses may be exceeded.

Flame straightening of EHS steels seem to have been performed without any problems in some cases, whereas in other cases it is evident that restrictions on use of flame straightening imposed on the fabricators by the oil companies, have led to problems with fit up.

In the cases where PWHT has been applied and the post weld heat treatment temperature has been kept at least 30°C below the steel tempering temperature (QT-steels), no problems with satisfying the strength requirements to the welded joints have been reported.

Gas cutting of the modern low carbon, low Pcm QT or TMCP steels in thicknesses at least up to 50 mm, can in general be performed without any risk of cracking problems under ordinary workshop conditions.

Grinding, milling and sawing of EHS steels may, however, lead to some greater wear of the tools than for ordinary normalized steels.

3.2 Welding

One of the most conspicuous trends in the development of structural steels in the last 15 years has been the ever increasing emphasis on improved weldability. This also holds for EHS steel.

The general experience from welding of these steels and in particular the QT steels, covers a wide range of applications including such as pressure vessels, hydro power penstocks, mobile cranes, forestry and farming equipment, bridges as well as special ships and offshore platform primary deck structure, modules and piles. However, the experience relevant to this study will as mentioned previously, be from the offshore industry and from the construction of icebreakers.

In general the experience with manufacturing in extra high strength steels shows that there are normally few problems associated with welding (1.5.9). The weldability of the modern steels in this strength is good due to low carbon contents and low contents of alloying elements as well as low content of impurities.

Weldability may be said to incorporate several elements. However, in this context the two most important ones are:

- safety against hydrogen induced cold cracking
- heat affected zone toughness

In the following these two main aspects of weldability are briefly discussed.

3.2.1 Risk of Hydrogen Induced Cold Cracking, Preheat Requirements

These steels are low carbon grades with carbon contents below 0.16% wt and currently most often below 0.12% wt. The Pcm[(1)] carbon equivalent formula has been found more appropriate (1.5.9 - 1.5.12) for evaluating the cold cracking susceptibility than the widely used CEIW[(2)] carbon equivalent formula.

Hence, for these steels the Pcm formula is used in specifications, new codes and standards. Limiting the Pcm value to maximum 0.22, see Table 3.2, has been found to ensure that these steels for most applications offshore can be welded with moderate (50°C) or no preheating in plate thicknesses below 40 - 50 mm corresponding to combined thickness below 100 mm.

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(1) Pcm = C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

(2) CEIIW = C+Mn/6+Cu/15+Ni/15+Cr/5+Mo/5+V/5

Table 3.2 Chemical Compositions

Type of st.	no.	Thickn. (mm)	CHEMICAL COMPOSITION (%Wt)														Carbon eq.	
			C	Si	Mn	P	S	Cr	Ni	Cu	Mo	V	Ti	Nb	Al	N	CEIIW	Pcm
QT	1	50	0.11	0.26	1.34	0.013	0.004	0.15	0.16	0.12	0.07	0.04	0.010	-	0.037	0.003	0.40	0.21
QT	2	''	0.09	0.44	1.34	0.014	0.002	-	0.40	0.24	-	-	-	0.019	0.043	0.009	0.38	0.20
TMCP	3	38	0.10	0.28	1.41	0.009	0.002	-	-	0.01	-	0.05	-	-	0.047	-	0.35	0.19
TMCP	4	50	0.03	0.24	1.45	0.005	0.002	-	0.47	0.52	-	-	0.014	0.041	0.027	-	0.34	0.14
TMCP	5	''	0.08	0.18	1.59	0.005	0.002	-	0.25	0.22	-	-	0.014	0.012	0.001	-	0.38	0.19
TMCP	6	50	0.07	0.17	1.59	0.006	0.003	0.03	0.25	0.20	0.01	0.01	0.014	0.001	0.001	0.0030	0.38	0.18
TMCP	7	''	0.07	0.23	1.47	0.009	0.003	0.04	0.36	0.20	0.01	0.01	0.007	0.001	0.028	0.0030	0.36	0.18
TMCP	8	75	0.07	0.23	1.49	0.006	0.002	0.02	0.39	0.11	-	-	0.010	0.010	0.030	0.0036	0.36	0.17
TMCP	9	38	0.07	0.26	1.35	0.011	0.003	-	0.14	0.14	-	-	0.007	0.016	0.030	0.0026	0.31	0.18

Testing of the steels for characterization of susceptibility for cold cracking is often performed using the modified Tekken or the JIS y-groove test method. The critical preheating temperatures to avoid cold cracking determined from this test are however, too stringent for application to practical multipass welds. As a rule of thumb (1.4.11) the preheating temperature can be reduced by about 50 - 75°C from that determined from the JIS y-groove test. However, it should be emphasized that such tests are always associated with great scatter.

Typical test results from testing of both normalized ($Re_{min} \geq$ 310 MPa) and high strength QT ($Re_{min} \simeq$ 500 MPa) for different plate thicknesses and Pcm values are shown in Fig. 3.1.

For welding the high strength steels (QT and TMCP) most common welding methods can be employed with the same equipment as for ordinary steels. Manual shielded metal arc welding (SMAW) as well as mechanized welding processes such as flux cored arc welding (FCAW) and submerged arc welding (SAW) are the most common welding processes.

As would be expected from their low carbon contents and Pcm values the CONRAC steels possess excellent resistance against cold cracking in the HAZ, and this is also supported by available fabrication experience.

As weldability is related to the weldment as a whole, however, the safety against cold cracking in the weld metal must also be considered in this context. This aspect is included in the following comments on the risk of cold cracking during welding of EHS QT steel of σ_y = 500 MPa, based on recent work at Veritec.

In this work the preheating required to avoid cold cracking in QT steel and normalized steel has been compared for two different situations:

- the two materials have the same section thickness
- the two materials have the same section strength

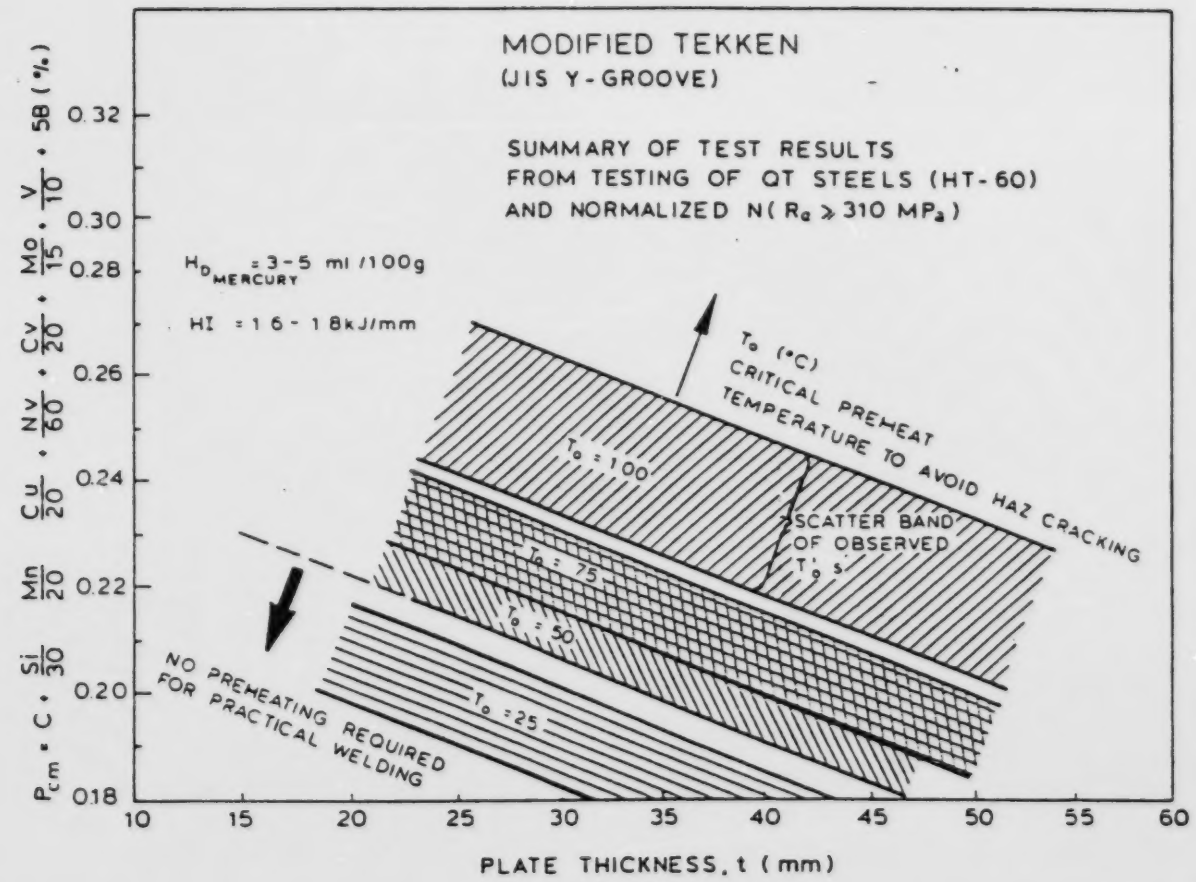

Fig. 3.1 Summary of Some Results from JIS Y-Groove Weld Cracking Testing Performed at Nippon Steel Corp., Sumitomo, Nippon Kokan and DnV

The comparisons were performed assuming two different welding consumable hydrogen potentials: H_{DM} = 10 ml/100g, and H_{DM} = 3 ml/100g.

Four levels of weld metal tensile strength were considered:

590 MPa (upper range for normalized steels)
620 MPa (matching strength for the QT steel)
660 MPa (slightly overmatching for the QT steel)
700 MPa (considerably overmatching for the QT steel)

The main findings are as follows:

- When preheating requirements are compared under conservative conditions with respect to weld metal diffusible hydrogen contents (H_{DM} = 10 ml/100g), the preheating level is largely determined by the weld metal strength (risk of weld metal cracking). When comparing the two types of steel for the same plate thickness under such conditions, welds in the QT steel may require about 60°C - 70°C higher preheating temperature than the normalized steel.

- When the comparison is made for the low hydrogen potential (H_{DM} = 3 ml/100g), the beneficial effect of the lower weld metal hydrogen content is clearly demonstrated. Under these conditions there will for practical situations be no difference in the preheating requirements for QT steel and normalized steel of the same thickness.

- If the higher strength of the QT steel can be fully utilized to give reduced plate thickness, the comparison becomes very favourable for the QT steel, since both lower preheating temperatures and less deposited metal (about 40% reduction for butt welds) will be required. This will have a considerable impact on the overall cost of welding which may be reduced by more than 40%.

3.2.2 HAZ Fracture Toughness

Since the early 1980's there has been considerable concern about the HAZ fracture toughness of low carbon microalloyed HS steels because of their tendency to develop local brittle zones (LBZ) in the HAZ. Such zones are primarily part of the fully transformed HAZ, i.e. the grain coarsened HAZ which may consist of ferrite sideplate/upper bainite microstructures. Now the chemical composition of the modern EHS steels are in many respects similar to these low carbon normalized HS grades. Furthermore, as the HAZ embrittlement occurs mostly in the fully transformed HAZ which is independent of the original plate condition, whether CONRAC, QT or normalized, HAZ embrittlement may occur to a similar extent in the EHS as in the normalized HS grades.

There are several factors which influence the HAZ toughness. Apart from the welding conditions the detailed chemical composition and degree of micro-segregation are considered the most important factors.

At the present position one has a good idea of what elements contribute positively resp. negatively to the HAZ toughness. None the less one cannot reliably predict the HAZ microstructure and HAZ CTOD fracture toughness from the knowledge of the detailed chemical composition. For the purpose of selecting steels with a low risk of developing LBZ one must still resort to actual testing of the steels in question.

When measuring HAZ CTOD fracture toughness it is difficult to obtain the required consistency in the test results to establish the correlation between the toughness and the welding conditions by using conventionally welded panels and the standard CTOD testing technique. In such cases the "bead-in-groove" testing method mentioned earlier in this report may be advantageous. This is the background for the recommendation of this technique in the Veritas Recommended Practice: "Unstable Fracture" (RP D404) for materials research and testing to establish the susceptibility of various materials for developing LBZ.

As discussed previously in paragraph 2.2.2 the toughness requirements for an EHS QT steel are more stringent as compared with the HS steels if both materials are utilized to the same degree with respect to their yield strengths. This applies also for the weld zone where the CTOD fracture toughness may be reduced locally due to presence of LBZ.

For the EHS QT restrictions on the maximum allowable arc energy/heat inputs for avoidance of brittle fracture initiation must be established by testing. Work performed by Veritec on such QT steels has shown that it is possible to select steels and optimum welding conditions to avoid brittle fracture initiation from LBZ at - 10°C. On the other hand this work also showed that if the brittle fracture initiation occurs in LBZ's in certain EHS steels, the brittle fracture may propagate far into the parent plate and is not always arrested in the fine grained HAZ as is generally the case with the HS normalized steels of the same CTOD fracture toughness. The reason is probably that for the same CTOD value more energy is available for propagating the brittle fracture in the EHS steels due to the higher loads at initiation in these stronger steels.

Although small scale CTOD fracture toughness tests indicate that the brittle fracture behaviour can be more critical for EHS QT steel than for HS steels, there still remains work to investigate the behaviour of the EHS QT steels under large scale conditions.

3.3 Post Weld Heat Treatment (PWHT)

3.3.1 General

The main purpose of performing PWHT of welded joints is usually to reduce residual stresses, which has the following favourable effects:

- improved fracture resistance
- increased resistance to stress corrosion cracking
- increased dimensional stability

In addition important beneficial effects will be obtained due to

- tempering of hardened parts of the HAZ miscrostructure
- reduction of hydrogen content.

Negative effects such as reduced toughness in parts of the weld zone may also occur. This is primarily due to precipitation processes in the HAZ and/or weld metal and thus depends on the chemical composition of the materials involved. In particular the type, amount, and combination microalloying elements is important in this respect.

3.3.2 PWHT of QT Steel

EHS QT steels may also be subjected to PWHT. As discussed in Section 2.2.1.2, however, care must then be exercised that the heat treatment does not lead to a loss of strength. This is the only major difference between QT-steels and normalized steels in connection with PWHT.

Generally, this important aspect is taken care of by manufacturers of QT steel plate expressing the warning that the PWHT temperature must always be well below the tempering temperature of the material. In addition, depending on the type and combination of microalloying elements, the PWHT temperature recommended by the steel manufacturer may be typically 20°C - 50°C below 600°C for certain types of steels. This is due to the risk of precipitation hardening that may deteriorate the impact and CTOD fracture toughness of the HAZ, especially for steels of vanadium contents > 0.08% Wt.

Precipitation hardening in vanadium-niobium microalloyed steels attains a maximum around 60°C, as was recently shown by an investigation performed at the Welding Institute. These findings are supported by work at Veritec, both on thick (50 - 100 mm) welded panels of normalized (σ_y = 460 MPa) and QT (σ_y = 690 MPa) steels. This work showed that subsequent to PWHT at 600°C the CTOD fracture toughness of the HAZ in these vanadium bearing steels deteriorated. The effect was found both by conventional CTOD testing and wide plate testing.

At the present time, however, it is in general not possible to assess the effect of PWHT on HAZ fracture toughness solely based on information about steel chemistry. This important point must therefore be checked experimentally.

For EHS QT steel several manufacturers recommend a PWHT temperature of 580°C. This is high enough to bring about considerable stress relaxation and still low enough to avoid softening effects. This tempeature is therefore regarded as good choice for PWHT of the QT steels considered here.

3.3.3 PWHT of CONRAC Steel

The CONRAC steels which are considered for application in ships and offshore structures have been accelerated cooled down to about 400°C and then allowed to cool in air to ambient temperature. Such steels can be exposed to PWHT without any significant drop in strength.

Also, due to the low level of microalloying elements most often used in CONRAC steels, PWHT does not normally lead to a reduction of HAZ toughness.

An example of base material properties before and after PWHT is given in Table 3.3 for a 50 mm CONRAC plate (Steel No. 4 in Table 1.3).

3.4 Experience with EHS Steels

In connection with the present study an inquiry regarding experience with fabrication in high strength steels was made to a number of offshore yards in Norway, one steel work in Sweden (SSAB), and a ship yard (GVA) in Sweden. This latter yard was included because it has experience with building of icebreakers where these steels have been used. In addition, another inquiry seeking detailed information on typical construction elements, their total weight and the potential for weight saving was directed to Norwegian offshore engineering companies and oil companies.

Table 3.3 Mechanical Properties of 50 mm CONRAC Plate Before and After PWHT (Steel No. 4, Table 1.4)

PHWT	None	Yes
Yield strength Re, MPa	484	478
Tensile strength Rm, MPa	574	569
Elongation A5, %	37	37
Charpy V. transv. at - 60°C	342	321

The former inquiry was seeking detailed information on fabrication experience with TMCP/QT steels (420 MPa $\leq Re_{min} \leq$ 599 MPa) with regard to:

- weldability and selection of consumables
- forming
- repair
- heat treatment/PWHT
- fabrication problems

The results of these two inquiries have been summarized in the present report and will serve as basis for the discussions on potential application of these steels in ships and offshore structures for Arctic and Subarctic service.

3.4.1 Availability of High Strength Steels Suitable for Arctic and Subarctic Service

Works Grades

The following works grades have been identified as potential candidates for use

in ships and offshore platforms with regard to the above mentioned yield strength range:

a) SHORALSIM 450 and 500 (Fabrique de Fer de Charleroi, Belgium.
b) OX 602 M (SSAB, Sweden)
c) XABO 500 (Thyssen, West Germany)
d) ROT 501 T (British Steel Corp., Great Britain)
e) WEL-TEN 60M/62M
   WEL-TEN 60 M-TIO
   (Nippon Steel Corp., Japan)
f) SUMITEN 60 LT (Sumitomo Metal Ind., Japan)
g) RIVER ACE 60/62M
   (Kawasaki Steel Corp., Japan)
h) NK-HITEN 60/62M
   (Nippon Kokan, Japan)

A common feature for these steels with regard to chemistry is a low maximum C-content (typically 0.12%) and thereby a low CE or Pcm-value, low maximum values of sulphur and phosphorus (typically 0.008% and 0.015% respectively) and relative narrow limits on grain refining and alloying elements. In addition high elongation requirements e.g. A5 $\geq$ 20% and severe requirement to toughness e.g. Charpy V-notch energy of 50 Joule (transverse) at - 60°C, are typical examples on mechanical properties specified for these steels.

To our knowledge, all of the above mentioned steel works have in general a satisfactory record of experience and are potentially fully capable of delivering the actual steel grade for use in ships and offshore platforms intended for Arctic and Subarctic service.

Base Metal Properties

The main body of fabrication experience in these steels (especially OX 602 M and RQT 501) are from fabrication of offshore modules and deck structures for service in

North Sea platforms. Hence, the toughness requirements, and the Charpy and CTOD testing temperatures are selected reflecting the service temperatures for these installations. In general this implies that the Charpy impact testing temperature has been $\leq$ - 40 (- 50°C) and the CTOD testing temperature - 10°C (1.4.1).

Now, for the present assessment the candidate steels are evaluated in the light of potential Arctic and Subarctic application for offshore structures and ships. Accordingly, Charpy impact test requirements as well as CTOD requirements must be adjusted to meet the severe service conditions encountered for such applications.

This means that the candidate steels must meet the toughness requirements for Charpy testing in the range from - 60°C to - 80°C and CTOD requirements at temperatures in the range of - 20°C to - 40°C.

Currently high strength steels ($Re_{min} \geq$ 420 MPa), in particular TMCP steels manufactured by Japanese steel mills, are available that can meet such toughness requirements at least in the parent metal. With respect to the weld metal and HAZ this will be discussed in Secs. 3.5.3 and 3.5.4 respectively.

In Tables 3.2, 3.4 and 3.5 chemical composition, mechanical properties and base metal CTOD data for a number of QT and TMCP structural steels from Japanese and European steels works are shown.

Table 3.2 shows typical chemical compositions of candidate steels. It is seen that these steels comprises C-Mn, low carbon steels with low alloying contents and low levels of mpurities as well as microalloying elements.

Another typical feature is a the low levels of carbon equivalents which improves weldability as well as toughness.

It is seen from Table 3.4 that five of the steels can easily meet a transverse Charpy impact toughness requirement of 50 J at - 60°C (- 80°). For the four other steels, although not reported in this table, there are good reasons to expect that they

Table 3.4 Mechanical Properties

Type of st.	no.	Thickn. (mm)	MECHANICAL PROPERTIES			
			Re (MPa)	Rm (MPa)	Impact toughness , CV (J)	Testingtemp. (°C)
QT	1	50	529	628	t/4: 158 t/2: 146	-40
QT	2	50	429	542	t/4: 210 t/2: 80	-60
QT	3	38	472	574	t/4: 228 -	-60
TMCP	4	30	477	578	t/4: 289 t/2: 202	-60
TMCP	5	50	512	591	t/4: 289 -	-60
TMCP	6	50	455	565	t/4: 278 -	-40
TMCP	7	''	481	597	t/4: 252 -	-40
TMCP	8	75	442	519	t/4: 289 -	-40
TMCP	9	75	480	578	t/4: 204 t/2: 129	-80

Table 3.5 Base Metal CTOD Fracture Toughness Data

Results from CTOD testing, transverse direction

Type	no.	Thickn. (mm)	Base metal CTOD test results , δ(mm)(Test temp. °C)
QT	1	50	0.96 m 0.74 m 0.42 u (-10)
QT	2	50	2.8 m 3.9 m 4.1 m (-10) 2.3 m 2.6 m 3.8 m (-20)
QT	3	38	>1.5 m >1.5 m >1.5 m (-10) >1.5 m >1.5 m (-40)
TMCP	4	30	2.5 m 1.7 m (-20) 1.0 m 1.7 m (-60)
TMCP	5	50	>1.47 m >1.49 m >1.45 m (-10) >1.5 m >1.5 m >1.5 m (-40)

m,u: classification of event according to BS 5762:1979

would also fulfil such requirement as the - 40°C Charpy values suggests upper shelf behaviour at toughness values $\geq$ 146J.

Also with respect to base metal CTOD fracture toughness, Table 3.5 it is evident that typical CTOD requirements such as $\delta_{cmin} \geq 0.25$ (1.4.1) which has been imposed for offshore structural welds, can be met in the base metal at testing temperatures (- 20°C - 40°C) expected for steels for Arctic and Subarctic service.

3.4.2 Experience with Fabrication in EHS Steels

The results of the inquiry made to a number of Norwegian yards and one Swedish shipyard, regarding their experience on fabrication welding of offshore structures and also icebreakers, have been summarized in Table 3.6 below, all QT steels.

The results confirm that the experience in welding these steels are in general positive. Welding consumables which are well known and have an excellent record also for fabrication of lower strength steels e.g. BS 4360 grade 50D/E and similar, can often be employed also for these steels. Of course, this applies when the requirements to Charpy impact testing temperatures are the same.

There has however, been expressed some sceptisism recently (1.5.13, 2.3.5) as to the potential for application of self shielded flux cored arc welding. The reason for this situation is mainly the lack of self shielded flux cored arc welding consumables appropriate for welding these steels.

In such case there may be some cost penalties associated with the potential loss of this highly efficient semi-automatic welding process. On the other hand, as seen from Table 3.6, gas shielded flux cored arc welding has been used for welding these high strength steels. This process can be used as an alternative to self shielded flux cored arc welding provided proprer wind shielding can be assured.

Nonetheless, it is still a question if any flux cored arc welding consumables can consistently meet both the strength and low temperature toughness requirements expected for Arctic and Subarctic service in offshore structures and ships.

Table 3.6 Some Results from the Inquiry Among Offshore and Ship Yards on the Experience Gained During Fabrication Welding of High Strength Steels $Re_{min} \geq$ MPa

Company	Type of construction	Steel	Thickness range (mm)	Welding process	Experience				
					Welding consumables	Weldability	Preheating	Repair rate	Fabrication problems
1	Equipment module Primary deck structure	BS 4360 55FM 55FMZ (RQT 501) (OX 602)	< 75	SMAW GFCAW SAW	Tenacito38R DWA 55L Ok 13.27/ OK 10.62	Good	tc≤60 30°C 60<tc<100 50°C 101<tc<180 100°C	Very low	None
2	Beams, Primary deck structure	BS 4360 55FM (RQT 501)	15-25	SMAW SAW	Ph88s Ok 13.27/ OK 10.62	Good	tc≤50 .. ~ 50°C	Normal	None
3	Critical elements of primary deck structure	WELDOX 500	50-60	SMAW SAW	Tenacito65R OE S3NiMo1 OP 121TT	Good	SMAW: 50°C SAW:100°C	Normal	Restr. on flamestr. can give problems with fit up
4	Process module	BS 4360 55FMZ	20-60	SMAW GFCAW SAW	OK 48.08 DII80Ni1 OK 12.32/ OK 10.62	Good	50-100°C dependent on tc	Normal	None
5	Ship, Icebreaker	OX 602	38-50	SMAW SAW	OK 73.68 OK 13.27/ OK 10.62	Excellent	15-20°C	Normal	None
6	L,T,I,U and box-profile beams for offshore	BS 4360 55FZM (OX 602)	35	SAW	OK 13.27/ OK 10.62	Good	50-70°C	Normal	None
7	Deck and end sections for module	BS 4360 55FZM (OX 602)	40-60	SMAW GFCAW	Ph88s,Ph75s MXA 55T DII80Ni1	Good	50-100°C	Higher than normal	Some magnetic arc blow

tc: Combined thickness according to BS 5135:1984

Otherwise, both for manual metal arc welding and submerged arc welding, consumables are available that can consistently satisfy strength and toughness requirements expected for such service. This will be discussed in Sec. 3.5.3.

As mentioned previously the weldability of the candidate steels are good as was demonstrated by their low Pcm carbon equivalent values shown in Table 3.2.

As seen from Table 3.6 this is also the general experience from fabrication in these steels. This implies that for ordinary fabrication welding low or moderate preheating levels can be maintained, and that even for highly restrained welds in thick section steel (50 mm), preheating temperatures $\leq$ 100°C are generally sufficient.

The experience with welding these steels also indicate that in most cases repair rates can be anticipated which are not higher than for normalized steels.

From Table 3.6 it is seen that few fabrication problems related to the use of high strength steels are reported.

The two problems shown in this table are firstly, problems with fit up claimed to be caused by restrictions in the use flame straightening and secondly, incidients of magnetic arc blow.

Oseberg Experience (TMCP Steels)

In Table 3.6 only experience with QT steels is reported. However, there are also some experience in Norway from fabrication welding of offshore deck structures in TMCP steels in connection with the Norsk Hydro Oseberg A and B projects. In addition Norsk Hydro has experience from the welding of the Oseberg B Jacket. A total of 65,000 tons of Norsk Hydro Grade I steel, supplied by Nippon Steel Corporation, was used for the Oseberg A and B projects (1.6.3). Although the TMCP steel was delivered to Norsk Hydro's Grade I steel specification ($t \leq 50$ mm: $Re_{min} \geq$ 340 MPa), the actual yield strengths were in most cases in excess of 420 MPa. Hence, the experience gained from this major offshore project is also relevant for the present report.

In summary the experience from the Oseberg project shows that very few problems which could be related to the particular type of steel and steel strength were encountered. The problems which occurred were some incidents of low intercritical HAZ CTOD toughness, a few reports of magnetic arc blow, incidents of distortion cracking in highly restrained single sided welded welds in heavy section thickness steel (75 mm plate), and problems with interpretation of UT signals. This was mainly due to the unfamiliarity of UT operators to the special features of controlled rolled and accelerated cooled steels in terms of anisotropy in UT wave velocities.

3.4.3 Service Experience

The use of EHS structural steels in offshore and ship structures has so far been limited, and cosnequently information regarding service experience is also limited.

It is known that the material in question has been used on the following offshore structures:

- BP Magnus — Constructed 1983
- BP Ula — Constructed 1986
- BP Gyda — Under construction
- Statoil Gullfaks C — Under construction

Regarding ships, icebreakers built by Goetaverken during 1985 should be of current interest. These ships are built under DnV's supervison for Swedish authorities, but are not classified by DnV.

So far no indication of negative experience in connection with the use of EHS steel has been reported. This applies both to offshore structures and ships.

3.5 Technical Points Still Under Discussion

The more important technical points still under discussion regarding the practical use of EHS steel in ship and offshore structures are briefly presented below.

3.5.1 Fatigue

It is well knnow that the fatigue strength of a welded structure, is not in general improved by increasing the strength level of the steel. This is primarily because stress concentrations resulting from the local geometry of the weld toe region, including the presence of naturally occuring small undercuts, lead to crack initiation early in the fatigue life. Hence, most of the fatigue life is spent on propagating the crack, and propagation is relatively insensitive to material strength.

This situation has so far largely prevented any extensive use of EHS steel in fatigue loaded structures such as ship hulls and jacket structures for offshore platforms.

There is now considerable interest in looking at possible ways of circumventing this problem in order to take more full use of EHS materials. Several methods have been proposed, the more important ones are as follows:

1) Grinding of the weld toe region.
2) TIG-dressing (local remelting) of the weld toe region.
3) Shot-peening of the weld toe region.
4) Use of favourably shaped forged or cast components/details to avoid welds being present in hot spot areas.
5) Use of high silicon electrodes which flow well and give a smoother and more benign transition between plate and capping bead.

All of these methods aim at increasing the initiation period and research has shown that they are capable of giving considerable improvements of fatigue strength. From a practical point of view, however, the methods (1) and (4) are considered the most realistic and also the ones likely to give most consistent results.

Otherwise economic considerations will of course often be of decisive importance whenever a fatigue improvement method is to be chosen in each individual case.

Another aspect that needs further clarification is the influence of cathodic protection (effect of absorbed hydrogen) on crack propagation rates, where some contradictory data exists.

3.5.2 SCC in Seawater Under Cathodic Protection

The detrimental effects of hydrogen dissolved in steel have been known for decades. Traditionally most attention has been given to hydrogen cracking (cold cracking) in the HAZ of welds, and the risk of hydrogen cracking (flaking) in heavy cast and forged components. More recently attention has also been given to possible effects of hydrogen entering nto steel structures under cathodic protection in seawater.

Even though the mechanism of stress corrosion cracking (SCC) may not be fully understood, it is generally agreed that SCC of cathodically protected high strength structural steel is caused by embrittlement through hydrogen entry into the steel. The risk of hydrogen induced stress corrosion cracking is determined by three main categories of variables.

Material Properties

Possible SCC is strongly dependent on the properties of the steel. Various workers (1.1.10, 1.1.11, 1.1.12) have shown that susceptibility to SCC increases with increasing material strength and hardness. Special attention is paid to welded joints due to the transformation and hardening promoted by the weld thermal cycle. In practice, hardness measurements of base material and weld zone have been used for assessing the SCC resistance.

A maximum hardness level of 325 HV5 has normally been specified for structure Re_{min} = 350 MPa steels such as BS 4360 grade 50 D/E. Gooch (1.1.10) has proposed to increase the maximum hardness level to at least 350 HV5, and also indicates that 400 HV5 should be safe for plain seawater exposure. This agrees well with experimental results obtained in a Joint Industry Research Project carried out by Veritec (1.6.15).

Furthermore, microstructure, alloying elements and non-metallic inclusions will have influence on the propensity to SCC (1.1.13, 1.1.14).

Mechanical Variables

Important mechanical variables are the stress level, stress intensity at weld discontinuities and stress mode. According to Gooch (1.1.13), the high tensile residual welding stresses in the weld area that remain in the material unless the fabrication is efficiently stress relieved, can increase the risk of cracking (1.6.16). Even with stress relief treatment (PWHT), a certain level of residual stress will remain.

Although PWHT does not completely remove the tensile residual stresses a beneficial effect of such heat treatment with respect to the susceptibility of the HAZ to SCC may result from tempering of the HAZ microstructure. The concomitant HAZ peak hardness reduction is in general expected to be considerable for the steels discussed here.

Environmental Variables

Several factors will determine the amount of atomic hydrogen at the steel surface. Cathodic protection is a key factor, since the hydrogen discharge rate increases as the cathodic polarization potential is displaced in the negative direction. To protect a structure from corrosion, the cathodic protection system is designed to polarize the steel to a potential more negative than - 800 mV rel Ag/AgCl. A negative limit of - 1050 mV rel Ag/AgCl is in general specified. Steels with a yield strength above 700 MPa are not recommended used below - 900 mV rel Ag/AgCl, according to Veritas Recommended Practice B401 (1.1.15). Another factor which will increase the amount of atomic hydrogen on the steel surface, is the presence of hydrogen sulphide. H_2S may possibly be produced by sulphate reducing bacteria (SRB) below the mud line or by marine fouling on the steel surface.

Extensive service experience has not shown SSC to be a problem for normalized steel of Re_{min} = 350 MPa. For EHS steel of Re_{min} = 690 MPa, however, recent cases

of service induced cracking in Jack Up rigs have been identified as SCC. These steels were in as-welded condition, polarized to a potential about - 1050 mV rel Ag/AgCl and had relatively high peak HAZ hardnesses (above 400 HV5).

So far, little specific work has been done in this field for steels in the intermediate strength range Re_{min} = 420 - 500 MPa, which are the topic of this report. The risk of hydrogen induced SCC occuring in this class of steel is not considered great, but there is a lack of data. Examples of applications where this could be of importance are tethers with girth welded mechancial connectors for tension leg platforms, highly stressed "as welded" nodes and other structural elements in offshore structures or ships. With the aim of rectifying the lack of relevant data for the SCC resistance of EHS steels in the yield strength range 420 - 500 MPa, Veritec has recently prepared a project proposal outlining necessary experimental work. The objective of this work is to establish threshold values for avoidance of SCC with respect to:

- Externally applied stress
- Cathodic protection potential
- Weld toe hardness.

3.5.3 Welding Consumables/Weld Metal Properties

As discussed in Sec. 3.4.2, the experience so far has indicated that in most cases well documented consumables which also have been used for the normalized structural steel grades can be used for EHS steels. However, this is valid for Charpy impact test requirements of minimum 35 J average at - 40°C and CTOD requirements typically 0.25 mm CTOD at - 10°C. For the test temperatures expected for Subarctic and Arctic service it is a fact that many of the commerically available consumables will have problems in meeting such toughness requirements.

The selection of welding consumables appropriate to welding of these steels is not only based on fulfilling requirements to mechancial properties. It is also intimately connected to the type of welding process, welding position and the welder appeal.

In addition to these factors there are basically four selection criteria which apart from weldability are related to the chemical composition, flux formulation and mechanical properties of the weld deposit.

These selction criteria comprise:

- The consumables should ideally match the chemical composition of the parent metal.

- For complete penetration joint welds which are stressed normal to the effective weld area, the weld deposit should sufficiently (10 - 20%) overmatch the yield strength of the actual steel i.e. not the minimum specified yield strength only.

- The weld deposit should have satisfactory impact toughness/fracture toughness.

- The diffusible weld metal hydrogen potential should be so low that cold cracking is avoided both in the parent metal (HAZ) and weld metal.

In this context it shall be remarked that the requirement for weld metal overmatching is still a subject of debate, however, in most situations it is a fair statement that weld metal overmatching will be beneficial for the fracture behaviour of welded joints.

There are several codes and standards available which provide some guidance for selection of filler metals. One code which is used rather extensively is ANSI/AWS D1.1-86 Structural Welding Code, Steel (1.1.16). This code states requirements to the filler metal in various applications with respect to welding processes, type of welded joints and direction and type of stresses.

One should also notice that this code does not explicitely give guidance to selection of filler metal when overmatching weld metal strength is desired from the

point of view of avoidance of localized plastic straining in the weld metal. This may occur in the presence of weld metal/HAZ cracks and under accidental loading. The protection obtained due to the yielding taking place in the parent metal rather than in the weld metal because of such overmatching, is becoming increasingly important to maintain when considering these high strength steels (1.6.17). For these steels this protection is no longer obtained automatically as is the case for the normalized steels with yield strengths ≈ 350 MPa. The reason being that all consumables used for welding of these latter steels almost always give overmatching yield strength weld metal.

For the 420 MPa minimum specified yield strength QT or TMCP steels, weld metal yield strength overmatching can for practical situations be maintained by selecting consumables conforming to one AWS strength class (> 10 ksi) higher than what is specified for matching filler metal requirements according to ANSI/AWS D1.1-86 (1.1.16).

On the other hand, following the principles of Table 4.1.1 of ANSI/AWS D1.1-86 the consumable classification appropriate to welding of the 450 MPa steels when there are requirements to matching weld metal strength, would comprise the filler metals conforming to AWS A5.5 E8015, E8016 and E8018 for SMAW, AWS A5.29 E80XT for FCAW and AWS A5.23 F8X-EXXX for SAW.

A review of the welding consumables appropriate to welding the high strength steels, giving matching and overmatching strength for the three most relevant welding processes, SMAW, FCAW and SAW have been performed by Veritec.

In conclusion it can be stated that for SMAW, gas shielded FCAW and SAW there are a number of candidate consumables which according to the manufacturers are capable of meeting the impact toughness requirements at - 60°C. However, the number of consumables are naturally considerably reduced from that which is available for the normalized steels. One must also consider that some of the candidate consumables may not be directly "off the shelf", hence somewhat longer delivery timesmust be taken into account. With respect to fracture toughness there is limited CTOD data for testing temperatures lower than - 10°C.

It is expected that for a major project where high strength steels are to be used for vessels or offshore structures for Arctic and Subarctic service, there will be necessary to conduct a test programme to select consumables that can consistently meet the requirements appropriate for the particular fabrication.

3.5.4 HAZ CTOD Fracture Toughness

From fracture mechanics considerations it can be demonstrated that for steels in the yield strength range from 350 - 500 MPa the toughness requirement in terms of critical CTOD-value is proportional to the yield strength for a given defect acceptance level.

Thus, the toughness requirements (or the defect acceptance criteria) for EHS steel (Re_{min} 420 - 500 MPa) will in general be more stringent than for a normalized steel provided both steels are utilized to the same degree with respect to their yield strength.

EHS weldments may possess satisfactory HAZ fracture toughness, although measurements typically exhibit a considerable amount of scatter of the results.

Typical results from testing of the grain coarsened HAZ and the inter-critical HAZ of modern TMCP and QT steels are presented in Tables 3.7 and 3.8, respectively. The steel numbers in these tables refer to the same steels as presented earlier in Sec. 3.4.

It is evident from these two tables that the HAZ in modern TMCP and QT may exhibit rather low critical CTOD values (< 0.20 mm) at testing temperatures - 10 to - 30°C.

Nonetheless, our experience is that even in the coarse grained HAZ close to the fusion line, which is considered the most critical region, high fracture toughness levels can usually be ensured by restricting the weld heat input (and hence the weld cooling time) to below a critical value. By using welding procedures that ensure a high degree

Table 3.7 Typical Test Results from Testing of the Grain Coarsened HAZ in Modern High Strength TMCP and QT Steels

Type	no.	Thickn. (mm)	Welding process	Arc Energy E (kJ/mm)	Prep	Temp. (°C)	CTOD, BS 5762 Bx2B, Notch through thickness δ (mm)
QT	1	50	MMA	1.5	K	-10	0.63 u, 0.50 u, 0.45 u, 0.49 u, 0.68 u, 0.20 u
QT	2	50	SAW	3.0	K	-10	0.24 u, 0.36 u, 0.20 u
QT	3	38	MMA	6.0	X	-20	0.15c, 0.40u
TMCP	4	30	SAW	4.5	K	-10	0.36 u, 0.48 u, 0.70 u, >0.90 m, >0.90 m, >0.91 m
TMCP	5	50	SAW	4.5	K	-30	1.7 m, 2.1 m,

c,m,u: classification of events according to BS 5762:1979

Table 3.8 Typical Test Results from Testing the Intercritical HAZ in TMCP and QT Steels

Type	no.	Thickn. (mm)	Welding process	Arc Energy E (kJ/mm)	Prep	Temp. (°C)	CTOD, BS 5762 Bx2B, Notch through thickness K-BxB , Surface notch V-, δ (mm)
TMCP	5	50	MMA	1.5	K	-10	0.37 u, 0.79 m, 0.90 m, >0.90 m, >0.93 m
TMCP	''	50	SAW	4.5	K	-10	0.81 m, 0.75 m, 0.90 m, >0.90 m, >0.90 m, >0.92 m
TMCP	6	50	FCAW	1.5	V	-10	1.9 m, 2.0 m, 1.8 m , 1.7 m, 1.7 m
TMCP	7	50	FCAW	1.5	V	-10	0.19 u, 1.70 m, 1.60 m, 1.50 m, 1.80 m
TMCP	8	75	FCAW	2.4	V	-10	0.08 c, 0.09 c, 0.12 c, 1.20 m, 1.20 m

c,m,u: classification of events according to BS 5762:1979

of HAZ refinemennt from subsequent weld passes, high CTOD fracture toughness can be obtained for most EHS steels.

In recent years much work on the CTOD testing of weld HAZ's has been published. This work has clearly shown that when this type of testing is analysed in more detail, several factors are found which can strongly influence the test results, and the situation thus becomes quite complex.

A key concept in this connection is the presence in the HAZ of local brittle zones (LBZ) which under certain conditions may initiate brittle fractures (pop-ins) during testing. Whether or not a pop-in is triggered in the coarse grained HAZ depends on several factors such as:

- The overall chemical composition of the steel; type and amount of alloying and micro-alloying elements.
- The degree of segregation in the steel. Increased segretations (degree and number of locally enriched areas) increases likelihood of forming LBZ's in the coarse grained HAZ.
- The amount of brittle material "seen" by the fatigue crack front.
- The dimensions and orientation of the LBZ relative to the fatigue pre-crack.
- Exact location of the pre-crack front with respect to the fusion line.
- The welding process used.
- The details of the weld thermal cycle.
- The strength of the weld metal, whether overmatching or undermatching (important for the stress that can build up prior to yielding).

- Chemical composition of the weld metal (local alloying effects near the fusion line).

In view of this complexity it is not surprising that questions are often asked about the real significance of pop-ins from LBZ's. It almost appears as if a clever experimentalist conducting the CTOD testing can generate or avoid pop-ins as he pleases, within quite wide limits regarding material and welding procedure.

These matters are presently much discussed. It is Veritec's opinion that a solution to this situation should be sought in an approach based on probabilistic fracture mechanics, and a project proposal has been prepared where such an approach is described in detail.

Nonetheless, with respect to the application of the EHS steels for ships and offshore structures for Arctic and Subarctic service, it is expected that requirements to HAZ CTOD toughness can be satisfied by careful selection of steel chemical composition and by restricting the welding heat input.

4. ECONOMIC POTENTIAL

4.1 Main Advantages

In connection with discussions of possible increased structural use of EHS steel it is commonly stated that the main incentive is weight saving. It is certainly true that weight saving is a key concept, but how this relates to economic advantages will necessarily vary from one project to the other, and the actual cost savings achievable are not easy to quantify on a general basis.

As an example the optimum use of EHS steel could lead to an offshore structure (or part of such a structure) being transportable by one barge instead of two, or that it can be installed by lifting rather than launching. This would no doubt have positive economic effects, but the actual savings obtainable would depend on the details of the specific project.

An example of this kind is the North Sea project Sleipner A, where Statoil will use high strength steel for the drilling rig and the drilling deck module. Due to the lighter structure thus made possible, the drilling rig and drilling deck module can be assembled at a yard onshore and the transportation and installation can be performed as one unit, saving valuable time offshore.

By constructing the drilling rig using high strength steel box columns the whole unit of total weight 1,600 tons can be lifted from the top of the drilling rig. Obviously, during this lifting operation the drilling rig will be subjected to much greater stresses than during normal service. However, by using these high strength steels and exploiting their high yield strength, this efficient and cost attractive approach is made feasible.

For North Sea offshore deck structures estimates (1.1.6) have shown that use of EHS steel can lead to weight savings of the order of 1,000 tons. As an example this weight corresponds to close to 4,300 m^2 of 30 mm thick plate which need not be:

- purchased
- transported
- stored
- cut to size
- formed to desired shapes
- prepared for welding (joint preparation)
- welded.

Obviously in such a situation there is a potential for significant cost reductions. Estimates for savings pr kg steel weight vary, but is often claimed to be in the range of U.S. $12.5 - 25/kg steel. Among other factors this figure will vary with at what point in the project the weight saving is implemented.

For considerable weight gains a "benign spiral" effect may be anticipated. As a top-side structure becomes more lightweight, the dimensions of the supporting structure can also be reduced. This leads to diminished wave loads, which may open up for further weight reductions.

During fabrication the cost benefits associated with the use of EHS steel are primarily related to the reduced plate thicknesses. In particular, when the yield strength can be fully utilized, the amount of weld deposit required for butt welds in the thinner EHS plate is significantly less than for normal strength material, theoretically it is proportional to the square of the normalized/EHS yield strength ratio. Thus, if a 350 MPa yield normalized steel is replaced by a fully utilized 480 MPa yield EHS steel, a 47% reduction of weld metal volume is theoretically possible.

If the strength of these steels is fully utilized to give reduced plate thicknesses this will have great impact on the need for preheating and PWHT as the plate thicknesses then can be limited to $\leq$ 50 mm for most applications for ships and offshore. The potential costs savings associated with this are expected to be significant as typical cost of preheating and local post weld heat treatment at least for Norwegian offshore yards, are of the order U.S.$125 and U.S.$250 respectively per m weld in plate thickness 40 - 50 mm.

However, it has been argued (1.5.13) that at least initially when a fabricating yard is starting to apply the high strength steels, it must qualify new welding procedures. This can for a major fabrication be in excess of U.S.$125,000.

Also there will be lack of data for CTOD fracture toughness. The considerable bank of data available for the normalized steels is now frequently used to obviate the need for PWHT, but this will not be possible for the high strength steels without testing until a similar amount of data has been collected for the EHS steels.

On the other hand by using EHS steels the section thickness can most often be restricted to below 40 - 50 mm, hence PWHT are not considered necessary. This has been used as one of the arguments for using EHS steels by welding engineers in British Petroleum (BP) who seem to have had considerable success in applying EHS steels (BS 4360 grade 55F) for three North Sea field development projects, i.e. the BP Magnus, the BP Ula and now recently the BP Gyda.

4.2 Estimated Saving Potential

Areas that have received special attention for weight saving exercises have been topside and sub-structure weights as it has been realized that each ton of reduced support structure or topside weight has a compound effect on overall cost as the weight reductions permit further savings in the structure.

However, it should be emphasized that these weight and cost savings are not at the expense of reliability or functionality. The design criteria used is still the same as before and in some cases more stringent. The process equipment supported is still able to meet all production requirements. The weight and cost savings are achieved by designing structures and facilities that are more efficient for their intended purpose, with less cost associated with items that are required only for fabrication or installation, such as pile guides and installation steelwork.

In the following the saving potential by use of extra high strength steel in offshore substructures and topside structures as well as other structural items is discussed and estimated for some selected types of structures and structural items.

4.2.1 Substructures

For substructures the effect of weight saving has both direct and indirect benefits. Clearly the direct benefit for a given structure is straight-forward to quantify, and is a result of the reduced material and fabrication cost. There are, however, a number of additional savings from a reduced jacket or other substructure weight that arise indirectly. These include:

- reduced fabrication schedule,
- more competitive fabrication bids arising from the increased number of fabrication yards and installation contractors able to undertake the work,
- reduced wave loading on the jacket leading to a reduced steel weight and piling requirements,
- reduced cathodic protection requirements,
- reduced inspection and maintenance costs, and
- reduced platform removal costs.

In (1.1.7) various options are considered for reducing the weight of typical North Sea steel jacket structures. Of the various options the weight saving potential by use of high strength steels is quoted to offer the second largest total potential weight saving (with the largest potential being the option with post-installed leg inserts).

In the example given for a 100 m water depth jacket BS 4360 grade 55EE with yield strength of 450 MPa has been compared with standard design grade 50D with yield strength of 355 MPa.

Due to the high fabrication cost of making welds at nodes satisfactory for fatigue performance, the use of high strength steel is limited to elements between nodes. All nodes are assumed to remain in grade 50D material. Even so, this option

offers the second largest total potential weight saving, and the savings are proportional to water depth. This is associated with a material and fabrication cost penalty.

This is however, a recommended option, particularly for a deep water jacket. It should be noted that because of the increased deflection at higher stresses, the weight saving is not directly related to material stress levels, and that the increased flexibility adversely affects dynamic amplification factors and fatigue levels. The weight saving potential for high strength steel is approximately 15% of the total jacket weight.

If the material and fabrication cost penalty is assumed to add 25% to the cost of high strength steel items (1.1.7), the weight saving of a typical 100 m water depth jacket can be estiamted to be 800 tonnes saved at a cost reduction of approximately U.S.$ 2,500/tonne (i.e. a total of U.S.$2 million).

4.2.2 Topside Structures

For several reasons the total deck weight of an offshore platform should be kept as low as possible. Not only is the fabrication cost of the deck itself increasing with increasing steel weight. The substructure is also significantly influenced by the total deck weight in most cases. The effect on a supporting structure increases rapidly with increasing depth.

The main weight component of topside is the structural steel. In (1.1.6) a study of offshore topside steel structures has been performed in order to find out how much the structural steel weight of a typical offshore topside can be reduced.

In order to get a reference for comparison an already designed platform has been studied. The structural design and analyses of the topside steel structure of Gullfaks A which is a combined drilling, production and quarters platform located on the Gullfaks field in the North Sea, were obtained from Statoil who is the operator of the platform. For selected parts of the platform the weights of the original parts are

compared with the weights of alternative designs. These parts are:

- Module Support Frame
- Wellhead Module
- Shaft Transitions
- Module Support Stools

The studies made in (1.1.6) have shown that it is possible to significantly reduce the weight of the load carrying parts of conventionally designed topside steel structures by different means. One of the main possibilities that has been investigated is the use of extra high strength steel, paricularly OX 602 with a yield strength of 500 MPa.

In the following the results of the study of different items are summarized (1.1.6):

Module Support Frame MSF

The module support frame (MSF) of Gullfaks A consists of a plate girder, which is made up of 10 m deep bulkheads with top and bottom flanges, which forms part of the upper and lower deck.

The study in (1.1.6) of the MSF is split up into two separate analyses of primary and secondary structure. With the aim of reducing the structural weight an alternative framing arrangement for the primary structure as well as a change to Extra High Strength (EHS) steel grade OX 602 have been studied. For the secondary structure only the possible weight reduction due to change to EHS is investigated.

The possibility of reducing the weight of the secondary structural elements is limited by the requirements for maximum deflection of stiffeners.

The original steel weight of the MSF is 8,900 tonnes of which the parts considered in (1.1.6) cover approximately 3,800 tonnes or 43% of the total steel weight.

The weight of the primary structure studied in (1.1.6) is 3,600 tonnes. By using an alternative stiffener arrangement a weight reduction of 12% (or 420 tonnes) is obtained. By using EHS an additional weight reduction of 19% is obtained corresponding to 605 tonnes further reduction of weight.

For a deck plating a theoretical weight reduction by use of EHS of 17% is reported.

Wellhead Module

The wellhead module is a steel frame module positioned by the MSF. The module contains three full decks and two part decks.

The study in (1.1.6) is split into separate analyses of primary and secondary structural elements.

The dimensions of the primary structure by use of EHS were reduced until the usage factors were the same as in the original design.

The possibility of reducing the weight of the secondary structural elements is limited by the requirement of maximum deflection of the stiffeners.

The structural steel weight of the module is approximately 1,000 tonnes of which 41% is included in the study made in 1.1.6.

The results show that it is possible to achieve a weight reduction of 17% (70 tonnes) for the considered parts compared to the original design by using EHS.

Shaft Transitions

The shaft transition areas form the transition between the top of the gravity base structure and the underside of the MSF.

An alternative design by use of EHS gives a total weight reduction of the shaft transitions of 18% or 64 tonnes.

Module Support Stools

The module support stools are placed on top of the MSF and supports the modules and distributes the module loads into the MSF.

By use of EHS the module support stools become 29% or 72 tonnes lighter than the original design.

A conclusion on the studies made in (1.1.6) is that by changing the steel from High Strength steel with yield strength of 325 - 340 MPa to Extra High Strength steel with yield strength of 500 MPa, reductions in the order of 15 - 30% are obtained.

The increase in dynamic stress levels due to the reduced thickness was shown not to cause any significant fatigue problems.

It is outlined in (1.1.6) that the studies are based on an existing design and that no major changes in the structural arrangements have been made. It is believed that the weight savings may be further increased if the structural designs are further optimized for the EHS steel grade.

Compressor Module

In (1.1.8) a study on weight saving of a compressor module by use of extra high strength steel with yield strength 690 MPa instead of high strength steel with yield strength 360 MPa has been carried out. The module has been divided into the following structural components which have been studied separately:

- deck plates
- plate stiffners and secondary trusses
- primary beams
- longitudinal and transversal trusses

The possible weight saving of each structural component has been estimated, and based on the results from these part studies the total module weight saving has been determined.

With the analyses approach selected and the assumptions made in each part study, it is indicated in (1.1.8) that the total module structural weight can be reduced by approximately 12%, corresponding to a total module weight reduction of approximately 6%.

4.2.3 Single Structural Items

In a report made by ARBED (1.1.9) on production and application of steel sections in steel grade FeE 460 with yield strength of 460 MPa the following estimations of weight savings on different structural items compared to use of steels with yield strength less or equal to 360 MPa are given:

Columns

When using columns in steel grade FeE 460, the average weight savings are about 22%. In some cases, e.g. for certain buckling lengths or different steel shapes, the savings may be much more pronounced. At the same time, the total area of the column can be reduced by about 25% in average, increasing by this way the effective area of the building.

Beams

Use of beams in FeE 460 leads on the one hand to weight savings of about 15% as compared to steel with yield strength 360 MPa when choosing the same beam web height, or on the other hand to a depth reduction of about 11%. For onshore applications the deflection problems can be solved by using composite beams, where the steel section is connected to a concrete slab by shear studs. For applications where composite beams are not relevant, the weight reduction of beams may be limited by the deflection requirements.

Frames

In industrial steel frame buildings, weight reductions of 30% have been reached compared to grade Fe 360 with yield strength of 235 MPa.

5. CONCLUSIONS

An assessment of the techno-economic feasibility of using high strength (420 MPa $\leq Re_{min} \leq$ 500 MPa) steels for ships and offshore structures, particularly with respect to Arctic and Subarctic conditions, has been performed.

For the assessment the experience gained primarily in fabrication of North Sea offshore structures using relatively small quantities of EHS steels, has been reviewed. Based on this experience, information from the open literature and Veritec in-house information the following main conclusions as to the potential for using EHS steels for offshore structures and ships constructed to operate under Arctic and Subarctic conditions have been reached:

- The experience so far with fabrication of offshore platform deck structures and modules in EHS steels is positive. Also fabrication experience of icebreakers in this type of steel is in general good.

- The service experience is limited.

- Oil companies that have used EHS steels on some projects tend to continue using EHS steels on new projects because of the positive fabrication experience.

- The motivation for applying EHS steels in offshore structures lies firstly in the potential for weight saving (6% - 30%), secondly for considerable reduction in deposited weld metal volume (theorectically < 47%) and thirdly for avoidance of PWHT (savings of the order U.S.$125 per m weld).

- The weldability and parent metal mechanical properties of the modern EHS steels (QT and TMCP) are in general good and are at least comparable to the properties of normalized 350 MPa yield strength steels.

- EHS steels that can meet base metal Charpy impact and CTOD toughness requirements at test temperatures expected for Arctic and Subarctic service are commerically available.

- Satisfactory HAZ CTOD fracture toughness can be achieved by careful selection of steel chemical composition and by restricting the weld heat input.

- The selection of welding consumables that can consistently fulfill toughness and strength requirements is considered a crucial point for the application of these steels. There are a number of consumables available that can meet the toughness requirements expected for Arctic and Subarctic service. However, the number is considerably reduced from that available for normalized steels. Also the relevant consumables may not be directly "off the shelf". Thus longer than normal delivery times have been experienced by the fabricators.

- It is not expected that SCC in the HAZ under cathodic overprotection potentials will be a problem. However, the present study has revealed that there is a lack of relevant data.

- Particular attention as to potential methods for improving the fatigue strength of EHS steel constructions must be given. The most relevant methods are grinding of the weld toe or use of favourably shaped forged or cast components/details to avoid welds in hot spot areas.

APPENDIX

REFERENCES AND INFORMATION SOURCES ON EXTRA STRENGTH STEEL

INFORMATION SOURCES ON EXTRA HIGH STRENGTH STEEL

1. OPEN LITERATURE

1.1 General survey articles
1.2 QT steel
1.3 CONRAC steel
1.4 Workshop procedures
1.5 Welding/weldability/consumables
1.6 Fracture toughness/local brittle zones

2. VERITEC REPORTS

2.1 Summary report QT project
2.2 Existing knowledge and design recommendations for high strength QT steel
2.3 Welding and weldability
2.4 Workshop procedures
2.5 Special features of QT steels and procedures for defect evaluation
2.6 Temper embrittlement and hydrogen effects

3. ABSTRACTS PROPRIETARY VERITEC REPORTS

1. OPEN LITERATURE

1.1 General Survey Article and Standards

1.1.1 Harrison, J.D.: "Material selection considerations for offshore steel structures", TWI Research Report 150/1981 July 1981.

1.1.2 Musgen, B.: "High strength quenched and tempered steels production, properties and applications". Metal Construction 1985 17 (8) 495-500.

1.1.3 Dolby, R.E.: "Steels for offshore construction". TWI Conference: "Towards rational and economic fabrication of offshore structures - overcoming the obstacles". London 22-23 Nov. 1984.

1.1.4 de Koning, A.C.: "Developments in materials and welding technology for offshore structures". Metal Construction 1985 17 (11) 727-734.

1.1.5 (Not used).

1.1.6 H. Bond, K. Lindberg and P.-O. Stark: "Light weight design of offshore topside structures", STU Project No. 83-3345, Stockholm, May, 1985.

1.1.7 Dr. N.J. Heaf and K.W. Paterson: "Weight saving possibilities in jackets and sub-structures", Offshore weight engineering conference, April 1987.

1.1.8 I. Scherf, S. Karlsson, P.-O.Stark, G. Solland and I. Lotsberg: "Weight saving in offshore modules using extra high strength steel with yield strength 690 MPa instead of normal high strength steel with yield strength 360 MPa", VERITEC Technical Report No. 85-3125, February 1985.

1.1.9 A. Frants, J.B. Schleich and J.P. Juncker: "Production and application of steel sections in steel grade FeE 460-Fritenar", Paper presented at the meeting in Copenhaguen of the Danish steel constructors, 17/11/1988.

1.1.10 Gooch, T.G.: Welding Institute Research Bulletin, Vol. 23 (8), 1982.

1.1.11 Treseder, R.S.: Welding Research Council Bulletin 243, November 1978.

1.1.12 Gooch, T.G.: Welding Journal Vol. 53 (7), 1974.

1.1.13 Brown, A. and Jones, C.L.: Corrosion 83, Paper 155, 1983.

1.1.14 McIntyre, P. and Banks, T.M.: European Offshore Steels Research Seminar Paper 19, 1978.

1.1.15 Veritas Offshore Standards Recommende Practice B401: "Cathodic Protection Design", 1986.

1.1.16 American Welding Society, Inc.: "Structural Welding Code, Steel". ANSI/AWS D1.1-86.

1.2 QT Steel

1.2.1 Musgen, B., Baumgardt, H., de Boer, H. and Janzon, W.: "High-strength steels with improved toughness and weldability for the fabrication of offshore structures". Paper presented at the 17th Annual OTC in Houston, Texas May 6-9, 1985.

1.2.2 Okano, S., Yano, K., Kaji, H., Kano, M. and Imazawa, H.: "Development of 690 MPa yield strength steel plates for arctic offshore structures". Kobe Steel Technical Report A-85B30, February 1986.

1.2.3 AWRA: "Quenched and tempered steel". Published by the Australian Welding Research Association 118 Alfred Street, Milsons Point, 2061, Australia, 1985.

1.2.4 Lefevre, G. and Dufrance, J.J.: "Offshore steel grades from 355 up to 450 N/mm^2 yield strength". Int. Seminar on Modern High Strength Steel in Marine Structures, Delft, the Netherlands, 28 October 1987. Organized by Technische Universitet Delft.

1.3 CONRAC Steel

1.3.1 Shiwaku, T., Shimohata, Takashima, S. and Kahji, H.:"YS 420 and 460 MPa strength steel plates for arctic offshore structures manufacturered by TMCP". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.3.2 Nakano, Y., Amano, K. and Kudo, J.: "Preheat and PWHT-free, 150 mm API 2W grade 60 steel plate for offshore structures". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.3.3. Matsuda, H., Onoe, Y., Moriyama, Koh, and Sekine, H.: "Development and future prospect of new controlled plate rolling technique-thermo mechanical control process". Nippon Steel Technical Report No. 21 June 1983.

1.3.4 Koda, M., Amano, Nakano, Y., Shiga, C., Tsubota, K., Kohno, Kumakura, Y. and Kaihara, S.: "Development of 420 MPa yield strength steel plate for arctic offshore structures". Proc. 6th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 87), Houston, Texas, 1987.

1.3.5 Sumitomo Metal Industries: "Sumitomo steel plates for offshore platforms". Sumitomo Metal Industries Ltd., April 1981.

1.3.6 Nippon Steel Corporation: "New Ti-treated high strength steel". NSC-02-10, January 1987.

1.4 Workshop Procedures

1.4.1 Culbertson, R.F.: "Offshore structural fabrication requirements". TWI Conference: "Towards rational and economic fabrication of offshore structures - overcoming the obstacles".

1.4.2 Dennin, G.: "Flammerichten von 5 bis 50 mm dicken Blechen aus verschieden Stahlen", DVS Berichte, Vol. 57, 1975, pp. 60-66.

1.4.3 Dennin, G.: "Einfluss des Flammenrichtens auf das Verformungs-verhalten und die Korrosionsbestandigkeit von Grobblechen aus unlegierten and legierten Stahle", Schweissen und Schneiden Vol. 28, 1976, No. 11, pp. 421 - 425.

1.4.4 Al-Erhayem, O. and Ussing, S.: "Straightenability of weldable low carbon high strength steels (QT-quenched and tempered)". Proceedings, Int. conf. on quality and reliability in welding, Hangzhou, China, September 1984, pp. 376 - 380.

1.4.5 Thiele, W-R.: "Geguge von hochfesten Feinkornbaustahlen nach Flammenrichtvorgangen". Schweissen und Schneiden, Vol. 36, 1984, No. 12, pp. 579-.

1.4.6 Weirich, G. et al: "Flamriktning - praktisk anvending och materialets paverkan". Svetsen, Vol. 43, 1984, No. 6, pp. 5-11.

1.4.7 Musgen, B.: "Umformen und warmenbehandeln schweissbarer baustahle". Thyssen Technische Berichte No. 1, 1981.

1.4.8 Al-Erhayem, O. and Ussing, S.: "Straightenability of weldable low carbon high strength steels (QT-quenched and tempered)". Proceedings, Int. Conf. on quality and reliability in welding, Hangzshou, China Sept. 1984, pp. 376-380.

1.4.9 Thiele, W-R.: "Gefuge von hochfesten feinkornbaustahlen nach flammenrichtvorgangen". Schweissen und Schneiden, Vol. 36, 1984, No. 12, pp.579.

1.4.10 Stewart, J.P.: "An introduction to flame straightening techniques". Met. Construction, Dec. 1987, pp. 692-693, and Jan. 1988, pp. 20-21.

1.4.11 Yurioka, N., Suzuki, H., Ohshita, S., Saito, S.: "Determination of necessary preheating temperature in steel welding". 63rd Annual Convention, AWS, April 1982.

1.5 **Welding/Weldability/Consumables**

1.5.1 "Consumables for higher strength steels". Metal Construction 1986 18 (6) 373-376.

1.5.2 Hart, P.H.M and Matharu, I.S.: "The influence of reduced carbon equivalent on HAZ cracking in structural steels". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.5.3 Yurioka, N., Suzuki, H., Ohshita, S. and Saito, S.: "Determination of necessary preheating temperature in steel welding". Welding Journal Research Supplement, June 1983, pp. 147-153.

1.5.4 Yurioka, N., Okumura, M., Kasuya, T. and Cotton, H.J.U.: "Prediction of HAZ hardness of transformable steels". Metal Construction 1987 19 (4) 217R-223R.

1.5.5 Okuda, N., Ogata, Y., Nishikawa, T., Aoki, T., Goto, A. and Abe, T: "Hydrogen-induced cracking susceptibility in high strength weld metal". Welding Research Supplement, Welding Journal 65 (1987) 5 pp. 141-146.

1.5.6 Lin, H.R. and Cheng, G.H.: "Hardenability effect of boron on carbon steels". Materials Science and Technology October 1987 Vol. 3, pp. 855-859.

1.5.7 Hoffmeister, H., Christensen, N. and Akselsen, O.M.: "Effect of heat input and preheating on hydrogen assisted weld joint cracking of a 0.13%C, 1.5%Mn, 0.032%Nb high strength steel of 50 mm plate thickness in the IRC test". IIW DOC IX-1492-87.

1.5.8 Lathabai, S. and Stout, R.D.: "Hydrogen-induced cracking in flux-cored electrode welds". Welding Journal, Welding Research Supplement, March 1983.

1.5.9 Bromsen, B. von: "Welding of extra high strength steels", IVF Resultat 89602 Mekanforbundets Forlag, Box 5506, Stockholm Sweden, January 1989.

1.5.10 Yurioka, N., Ohshita, S., Tamehiro, H.: "Study on carbon equivalents to assess cold cracking tendency and hardness in steel welding". AWRA, Melbourne, March, 1984.

1.5.11 Graville, B.A.: "Cold cracking in welds in HSLA steels", Int. Conf.: "Welding of HSLA microalloyed structural steels", Rome, November 1976.

1.5.12 Bryhan, A.J.: "The effect of testing procedure on implant test results", Welding Journal Res. suppl. 60, September 1981, pp. 169 - 176.

1.6 Fracture Toughness/Local Brittle Zones

1.6.1 Wastberg, S.: "Engineering significance of short cracks located in local brittle zones". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.6.2 Chijiwa, R., Tamehiro, H. and Hirai, M.: "Extra high toughness titanium-oxide steel plates for offshore structures and line pipe". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.6.3 Harneshaug., I.S., Valland, G., Gundersen, K. and Roland, M.: "HAZ fracture toughness in low carbon, controlled rolled and accelerated cooled steel used in North Sea offshore structures". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.6.4 Denys, R., Dhooge, A.: "Mechanical tensile properties of weld simulated HAZ microstructures in normalized, quenched-tempered and TMCP low carbon manganese steels". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.6.5 Denys, R. and McHenry, H.I.: "Local brittle zones in steel weldments: an assessment of test methods". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.6.6. Devillers, L., Kaplan, D. and Maas, E.:"Influence of local brittle zones on plate toughness application to welded structures". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.6.7 Hanus, F.E.: "Influence of width of weld simulated coarse grained zones on the Charpy transition curve". Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.6.8 Ahrengot, N.O. and Nielsen, K.: "The influence of copper and nickel on weldability in terms of toughness and microstructure in HAZ of thick, high strength microalloyed steel plate". Proc. Conf. The Fourth Scandinavian Symposium on Materials Science, NTH, Trondheim, August 25-26, 1986.

1.6.9 Grong, Ø. and Akselsen, O.M.: "HAZ toughness of microalloyed steels for offshore". Metal Construction 1986, 18 (9) 557-562.

1.6.10 Bhole, S.D. and Billingham, J.: "Effect of heat input on HAZ toughness in HSLA steels". Netaks Technology September 1983, Vol. 10 363-367.

1.6.11 Thaulow, C., Pauw, A.J., Gunleiksrud, A. and Naess, O.J.: "Heat affected zone toughness of a low carbon microalloyed steel". Metal Construction 1985 17 (2) 94R-99RR.

1.6.12 Haze, T. and Aihara, S.: "Influence of toughness and size of local brittle zone on HAZ toughness of HSLA steels:. Proc. 7th Int. Conf. on Offshore Mechanics and Arctic Engineering (OMAE 88), Houston, Texas, 1988.

1.6.13 Akelsen, O.M., Grong, Ø. and Solberg, J.K.: "Structure property relationship in intercritical heat affected zone of low-carbon microalloyed steels". Materials Science and Technology August 1987 Vol. 3 pp. 649-655.

1.6.14 Aihara, S. and Haze, T.: "Influence of high carbon-martensitic island on crack-tip opening displacement value of heat-affected zone in HSLA steels". Paper presented at the TMS Annual Meeting Phoenix, Arizona January 25-28, 1988.

1.6.15 Lunde, P.G. and Tronskar, J.P.: "Environmentally induced cracking in the heat affected zone of modern structural steels". Veritec Report No. 834-3247.

1.6.16 Clark, J.N. and Meyers, J.: Materials Science and Technology, Vol. 4 (7), 1988.

1.6.17 Denys, R.M.: "Fracture testing of weldments in relation to local brittle zones". International Seminar: "Modern High Strength Steel in Marine Structures". Delft, the Netherlands, 28/10/1987.

2. VERITEC REPORTS (Confidential until September 1989)

2.1 Summary Report QT Project

2.1.1 VT Report No. 87-3586.

2.2 Existing Knowledge and Design Recommendations for High Strength QT Steel

2.2.1 VT Report No. 86-3602

2.3 Welding and Weldability

2.3.1 VT Report No. 86-3675

2.3.2 VT Report No. 87-3474

2.3.3 VT Report No. 84-3521

2.3.4 VT Report No. 87-3195

2.3.5 VT Report No. 88-3329

2.4 Workshop Procedures

2.4.1 VT Report No. 86-3423

2.4.2 VT Report No. 87-3016

2.4.3 VT Report No. 88-3294

2.4.4 VT Report No. 88-3294

2.5 Special Features of QT Steels and Procedures for Defect Evaluation

2.5.1 VT Report No. 87-3080

2.5.2 VT Report No. 88-3079

2.5.3 VT Report No. 86-3687

2.5.4 VT Report No. 88-3151

2.5.5 VT Report No. 88-3330

2.5.6 VT Report No. 88-3333

2.5.7 VT Report No. 88-3029

2.6 Temper Embrittlement and Hydrogen Effects

2.6.1 VT Report No. 87-3058

2.6.2 VT Report No. 87-3079

ABSTRACTS PROPRIETARY VERITEC REPORTS

[2.1.1]

Rapport/Report

VERITEC

Dato/Date	Avd./Dept	Prosjektnr./Project No
87.10.01	VT31	4203209

Godkjent av/Approved by

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Rapporterende kontor/Reporting Office: BERGEN STAVANGER

Klient: Oppdragsgiver/Client: Sponsor — Klient ref./Clients ref

Esso Norge, Norsk Hydro, Norske Shell,
SSAB, Statoil, Det norske Veritas

Rapporttype/Type of Report

Technical

Sammendrag/Summary

Three QT steels of min. specified yield strength 500 MPa have been studied. The programme has consisted of the folloving part projects and main activities:

QT-1 : Welding and veldability
Hardenability and softened zones
Weld cracking tests
HAZ fracture toughness

QT-2: Workshop procedures
Gas cutting
Cold deformation and ageing

QT-3: Mechanical properties, special features
Cyclic stress-strain response
Procedures for defect evaluation
Effects of softened zones in HAZ

QT-4: Process variables in the steelvorks
Heat treatment sensitivity study
Temper embrittlement
Effects of hydrogen

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
87-3586	

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH QT
STEEL IN OFFSHORE STRUCTURES.

SUMMARY REPORT

Utført av/Work carried out by

G. Wold, J.P. Tronskar
S. Palm, A. Karlsen

Verifisert av/Work verified by

Dato for siste revisjon: Date of last rev.	Rev No.	Antall sider:

4 indekseringsterme* (på engelsk)/4 indexing terms

- QT STEEL
- WELDING
- MECHANICAL PROPERTIES
- FRACTURE TOUGHNESS

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TECHNICAL REPORT

Report No. 86-3602	Subject Group E3, D91	Department 421	Project No. 4213141

Date: 27.10.1986

Title of Report:
EXPLOITING HIGH STRENGTH QT STEEL IN OFFSHORE STRUCTURES
Existing Knowledge and Design Recommendations for High Strength QT Steel.
Technical Report No. QT-3.1

Approved by:
Stig Wästberg
Stig Wästberg
Head of Section, Materials and Structural Components

Client/Sponsor of project:
Esso Norge, Norsk Hydro, Swedish Steel, Det norske Veritas, Statoil, Shell Norge

Client/Sponsor ref.

Work carried out by:
Tor-Bjørn Larsson

Reporter's sign.

Summary

This report covers the literature survey of the Part Project QT-3 of the JIP project "EXPLOITING HIGH STRENGTH QT STEEL IN OFFSHORE STRUCTURES". The survey deals with the following aspects of QT structural steels:

- Treatment in design rules, codes and standards
- Mechanical properties, static and cyclic
- Fracture toughness
- Fatigue properties
- Fabrication experience.

4 indexing terms:

QT STEELS
DESIGN
MECHANICAL PROPERTIES
LITERATURE STUDY

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TECHNICAL REPORT

Report No	Subject Group	Date	Project No
86-3675	E3	15.12.86 / Department 420	421QT13

Title of Report
Exploiting High Strength QT Steel in Offshore Structures.
Activity 1.3 Softened Zones.

Approved by
Stig Wästberg
Stig Wästberg
Head of Section, Materials and Structural Components

Client/Sponsor of project
Esso Norge, Norsk Hydro, Shell, Statoil, SSAB, Det norske Veritas

Client/Sponsor ref.

Work carried out by
J.P. Tronskar

Reporter's sign
Jan P. Tronskar

Summary

An investigation has been performed to study the hardening behaviour of the HAZ in three QT steels of minimum specified yield strength 500 MPa.

The work also comprised a study of the propensity of these steels for sub-critical HAZ softening.

It is concluded that in terms of HAZ hardening response to weld thermal cycles, the steels tested behave similar to modern normalized structural steels of grade St 52-3N, although the maximum HAZ hardness can be expected to be higher than for such steels dependent on the carbon content.

Substantial HAZ softening was indicated by hardness measurements.

On the otherhand, the influence of the soft zones on the transverse weld load bearing capacity was demonstrated by tensile testing of 3 mm thin (sub-size) tensile specimens to be small. Reductions of $\leq$ 7% in U.T.S. were found for weld cooling times, $\Delta t_{8/5} \leq 63.3$ seconds. This was considered not to be of any practical importance for the plate thicknesses likely to be employed for fabrication of offshore structures ($\geq$ 25 mm).

4 indexing terms

QT-STEELS
HEAT AFFECTED ZONE
HARDENABILITY
SOFT ZONES

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[E3.2]

Rapport/Report

VERITEC

Dato/Date	Avd./Dept.	Prosjektnr./Project No
7 July 1987	VT31	421QT15

Godkjent av/Approved by

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Klient, Oppdragsgiver/Client, Sponsor: Esso, Norsk Hydro, Shell, SSAB, Statoil, Det norske Veritas

Klient ref./Clients ref.:

Rapporttype/Type of Report: Technical Report

Sammendrag/Summary

Weldability testing (JIS y-groove test method) of three modern low P_{CM} value QT-steels of min. specified yield strength 500 MPa has been performed.

Two plate thicknesses 25 and 50 mm were tested and the test welds were deposited using gas shielded flux cored arc welding (FCAW) with a basic flux type wire. The test welds were deposited at two different heat inputs 0.9 and 1.8 kJ/mm.

The hydrogen potential of the consumables was 3 ml/100 g of deposited metal.

VERITEC Rapportnr./Report No	Emnegruppe/Subject Group
87-3474	E3

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH QT-STEELS IN OFFSHORE STRUCTURES

ACTIVITY 1.4 WELD CRACKING TESTS

Utført av/Work carried out by

Jens P. Tronskar and H. Ulle

Jan P. Tronska Hugo Ulle

Verifisert av/Work verified by

G. Wold Gunnar Wold.

Dato for siste revisjon/ Date of last rev.	Rev.No.	Antall sider/ Number of pages
		63

4 indekseringstermer (på engelsk)/4 indexing terms

- QT-STEEL
- WELDABILITY
- HEAT AFFECTED ZONE
- HYDROGEN INDUCED CRACKING

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TECHNICAL REPORT

Date: 5.10.1984			
Report No.: 84-3521	Subject Group: E-3	Department: Vt-42	Project No.: W9C001
Title of Report: Technical Report No. 5 STUDY ON THE WELDABILITY AND HARDENABILITY OF A MODERN LOW CARBON EXTRA HIGH STRENGTH QT STEEL		Approved by: C.F.G. Baxter, Head of Section for Welding Technology	
Client/Sponsor of project: JIP A13: "Fabrication and Service Induced HAZ cracking in modern steels for offshore structures"		Client/Sponsor ref.	
Work carried out by: J.P. Tronskar and T.B. Larsson		Reporter's sign.	

Summary

This report covers the work undertaken to study the weldability of a moder low carbon (0.08%) extra high strength QT steel.

It was found that the International Institute of Welding carbon equivalent failed to describe the weldability, whereas the Ito and Bessyo carbon equivalent proved to be more appropriate.

Despite the low carbon content the steel was found to have a high hardenability, a consequence of the alloy and in particular the boron addition.

4 Indexing terms

LOW CARBON STEEL
EXTRA HIGH STRENGTH
QUENCHED AND TEMPERED
WELDABILITY

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Rapport/Report

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Dato/Date	Avd./Dept.	Prosjektnr./Project No.
20 May 1987	VT31	421QT15

Godkjent av/Approved by

Stig Wästberg

S. Wästberg
Head of Section

Klient, Oppdragsgiver/Client, Sponsor: Esso, Norsk Hydro, Shell, SSAB, Statoil, Det norske Veritas

Klient ref./Clients ref.:

Rapporttype/Type of Report: Technical Report

Sammendrag/Summary

An investigation has been performed to study the CTOD fracture toughness at -10°C of the grain coarsened and sub-critically reheated HAZ in three 500 MPa minimum specified yield strength QT-steels.

The work was carried out using "bead-in-groove" weldments. The special testing technique applied has been developed by Det norske Veritas (DnV) for testing the CTOD fracture toughness of locally embrittled regions of weldments.

The three steels tested responded significantly different in terms of CTOD fracture toughness obtained at various weld cooling times between 800 and 500°C ($\Delta t_{8/5}$).

When the welding conditions were varied such as to give weld cooling times, $\Delta t_{8/5}$ between 3.6 and 16.5 seconds, the test method was found to discriminate between the steels in terms of critical weld cooling time for transition from ductile to brittle fracture behaviour of the grain coarsened HAZ.

The observed differences in response to variations in the weld cooling times, were qualitatively in agreement with the behaviour expected based on the different base metal chemical compositions.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
87-3195	E3

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH QT-STEELS IN OFFSHORE STRUCTURES

ACTIVITY 1.5 HAZ CTOD FRACTURE TOUGHNESS

Utført av/Work carried out by: Jens P. Tronskar, H. Ulle and T.B. Larsson

Jens P. Tronskar Tarje Ulle

Verifisert av/Work verified by: G. Wold G.Wold

Dato for siste revisjon/ Date of last rev.	Rev.No.	Antall sider/ Number of pages
14.09.87	1	113

4 indekseringstermer (på engelsk)/4 indexing terms

- QT-STEEL
- HEAT AFFECTED ZONE
- CTOD FRACTURE TOUGHNESS
-

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Dato/Date	Avd./Dept.	Prosjektnr./Project No.
28.09.88	VT/31	31423501

Godkjent av/Approved by

Stig Wästberg

Stig Västberg
Head of Section

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Klient, Oppdragsgiver/Client, Sponsor	Klient ref./Clients ref.	Rapporttype/Type of Report
SINTEF	T. Håbrekke	Technical

Sammendrag/Summary

A review of relevant literature and steel specifications has been conducted to prepare tentative steel specifications for the research project: "Welding of EHS steels" to be undertaken by SINTEF. This research project will consider EHS structural steels with minimum specified yield strengths 450 and 650 MPa.

The work reported here also comprises a review of potential welding processes and welding consumables appropriate to welding these steels.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
88-3329	E3

Rapporttittel/Title of Report

Welding of extra high strength steels - selection of test materials and welding consumables

Utført av/Work carried out by

J.P. Tronskar and H. Heiro

Verifisert av/Work verified by

G. Vold

Dato for siste revisjon/ Date of last rev.	Rev.No.	Antall sider/

4 indekseringstermer (på engelsk)/4 indexing terms

- EXTRA HIGH STRENGTH STEEL
- SPECIFICATION
- WELDING PROCESS
- WELDING CONSUMABLES

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TECHNICAL REPORT

Report No. 86-3423	Subject Group E3	Date 22. December 1986	
		Department 420	Project No. 4203207

Title of Report
EXPLOITING HIGH STRENGTH QT STEELS IN OFFSHORE STRUCTURES.
Activity 2.1 Gas cutting

Approved by
Stig Wästberg
Stig Wastberg
Head of Section

Client/Sponsor of project
Esso Norge, Norsk Hydro, Shell, Statoil, SSAB, Det norske Veritas

Client/Sponsor ref

Work carried out by
G. Wold, O. Haukås Eide, T. Kristoffersen

Reporter's sign.
G. Wold O. Haukås Eide T. Kristoffersen

Summary

Gas cutting of three QT steels of min. specified yield strength 500 N/mm² has been studied with regard to risk of cracking, and hardness of the gas cut edge.

Plate thicknesses were 25 and 50 mm. Under none of the experimental conditions used was cracking detected.

Bending of plate samples with free gas cut edges over a former diameter D = 3·t (t = plate thickness) did not lead to cracking on the tension side of the samples. However, during bending the gas cut edges developed shallow surface fissures, up to 0.25 mm deep.

No systematic difference between the three steels investigated has been found regarding response to gas cutting and subsequent bending operations.

4 indexing terms
QT-STEELS
GAS CUTTING
FORMING

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Dato Date	Avd. Dept	Prosjektnr. Project No
06.01.1987	31	4203207

Godkjent av Approved by

Stig Wästberg
Head of Section

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Esso Norge, Norsk Hydro, Shell, Statoil
SSAB, Det norske Veritas

Rapporttype Type of Report

Technical Report

Sammendrag Summary

Tensile testing and Charpy V-notch impact testing of three QT steels of minimum specified yield strength 500 N/mm has been carried out.

Testing was conducted in the as received condition and after various deformation and ageing treatments.

The work has demonstrated that the common forming operations involving moderate cold deformation can safely be used for the investigated steels.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
87-3016	E3

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH QT STEELS IN OFFSHORE STRUCTURES

Activity 2.2 Cold deformation and ageing

Utført av/Work carried out by

G. Wold, T. Kristoffersen

Verifisert av/Work verified by

4 indekseringstermer (på engelsk)/4 indexing terms

- QT Steel
- Cold Deformation
- Ageing
- Mechanical Properties

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02.09.1988	VT 31	311055

Godkjent av/Approved by

for
Stig Västberg
Head of Section

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Klient, Oppdragsgiver/Client, Sponsor	Klient ref./Clients ref.	Rapporttype/Type of Report
Esso Norge, Norsk Hydro, Statoil		Technical

Sammendrag/Summary

The effects of flame straightening on mechanical properties of two high strength QT steels (Re ≥ 500 MPa) have been studied.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
88-3294	E3

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH QT STEEL
IN OFFSHORE STRUCTURES

Activity E-1 Flame straightening
of QT steels

Utført av/Work carried out by

G. Wold, T. Kristoffersen, H. Ulle

Verifisert av/Work verified by

Dato for siste revisjon/ Date of last rev.	Rev.No.	Antall sider/

4 indekseringstermer (på engelsk)/4 indexing terms

- HIGH STRENGTH STEEL
- FLAME STRAIGHTENING
- MECHANICAL PROPERTIES
-

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Dato/Date	Avd./Dept.	Prosjektnr./Project No.
11.02.87	31	4213141

Godkjent av/Approved by

Stig Wästberg

Stig Wästberg
Head of Section, Strength of Materials and Structural Components

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Klient ref./Clients ref.:

Rapporttype/Type of Report: Technical

Sammendrag/Summary

This report covers the testing of the cyclic stress-strain response of QT steels. The work performed belongs to Part Project QT-3 of the JIP project "EXPLOITING HIGH STRENGTH QT STEEL IN OFFSHORE STRUCTURES". The work comprised cyclic straining of material specimens at varying load magnitudes and load ratios followed by tensile testing. The yield strength, tensile strength and ductility of cyclically strained material was compared with the properties of unstrained material. Finally the influence of cyclic straining on the mechanical properties of the examined class of QT steel was assessed as a function of the plastic component of the cyclic loading.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
87-3080	E3

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH QT STEEL IN OFFSHORE STRUCTURES

Cyclic stress-strain response on mechanical properties

Technical Report No. QT-3.2

Utført av/Work carried out by

Tor-Björn Larsson

Verifisert av/Work verified by

Stefan Palm

4 indekseringstermer (på engelsk)/4 indexing terms

- QT STEEL
- CYCLIC LOADING
- TENSILE TESTS
- MECHANICAL PROPERTIES

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Dato / Date	Avd/Dept	Prosjektnr/Project No
12.02.1988	VT31	311034

Utført av/Approved by

Stig Wästberg

Stig Västberg
Head of Section

Oppdragsgiver/Client: Sponsor — Klient ref./Clients ref.

Esso, Norsk Hydro, Shell, SSAB
Statoil, Det norske Veritas

Rapporttype/Type of Report

Technical report

Sammendrag/Summary

The purpose of this investigation was to evaluate the conservatism of the CTOD design curve for high strength QT-steels.

Wide plate specimens with surface cracks, having the crack tip located in the HAZ of the bead-in-groove weld, were tested at -10°C. Small scale tests with the notch tip at the same location were also tested.

The occurrence of pop-in was significantly higher in the small scale bending tests than in the wide plates in tension.

The CTOD design curve produced safe predictions of the behaviour of the wide plate specimens when the result from the small scale specimens were used as input.

VT31/R/652/

VERITEC Rapportnr/Report No	Emnegruppe/Subject Group
88-3079	D7

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH QT STEELS
IN OFFSHORE STRUCTURES.

Activity 3.3 Procedures for defect evaluation.
Wide plate testing.

Utført av/Work carried out by

A. Karlsen, H. Ulle

Verifisert av/Work verified by

S. Palm

4 indeksenngstermer (på engelsk)/4 indexing terms

QT-STEEL
CTOD DESIGN CURVE
WIDE PLATE TESTING

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TECHNICAL REPORT

Report No. 86 - 3687	Subject Group E3, E6	Date 15.12.1986	
		Department 421	Project No. 4213141
Title of Report EXPLOITING HIGH STRENGTH QT STEELS IN OFFSHORE STRUCTURES Activity 3.4. Influence of Softened Overtempered Zones in the HAZ on the Strength of QT Steel Weldments.		Approved by Stig Wästberg Stig Wästberg Head of Section, Materials and Structural Components	
Client/Sponsor of project Esso Norge, Norsk Hydro, Shell, Statoil, SSAB, Det norske Veritas		Client/Sponsor ref.	
Work carried out by S. Palm & P. Hammersberg		Reporter's sign. Stefan Palm	

Summary

The effect on the elastic limit and the ultimate load carrying capacity of plate butt welds in high strength quenched & tempered steels of softened overtempered zones in the HAZ is determined. Two joint preparations, double-V and single U, are included in the investigation. Both tensile and bending loads are considered.

The results have been obtained by means of non-linear elastic-plastic FEM-analyses.

4 indexing terms

STRUCTURAL STEELS
QT STEELS
WELDING

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Dato/Date	Avd./Dept.	Prosjektnr./Project No
15.6.1988	31	311040

Godkjent av/Approved by

Stig Wästberg

Stig Wästberg
Head of Section

Klient, Oppdragsgiver/Client, Sponsor	Klient ref./Clients ref.	Rapporttype/Type of Report
Saga Petroleum a.s	G.E. Eide	Technical

Sammendrag/Summary

The SNORRE TLP tether design, material selection, manufacturing, assembling and installation require a high standard of workmanship to give satisfactory performance in the severe service conditions in the North Sea. A particular aspect of material properties is that of ensuring adequate fracture toughness also in the presence of hydrogen developed during cathodic protection in the sea water.

This aspect has been addressed in the work reported here, which consists of several special tasks conducted to assess the feasibility of obtaining crack tip opening displacement (CTOD) fracture toughness exceeding the minimum requirements of the SAGA Standard Specifications RSP-0126 "Manufacturing of Steel Forgings for Tether Components" and RSP-0127 "Manufacturing of welded Quenched and Tempered Pipe". Two candidate 460 MPa minimum specified yield strength QT steels have been tested, one representing rolled tether pipe material and one representing material for forged tether components.

The tests performed show that ductile fracture behaviour and consequently high CTOD values can be obtained in the parent metal and in the weld zone for circumstances simulating the service conditions of the tethers.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
88-3151	E3

Rapporttittel/Title of Report

SNORRE TLP - SCREENING TEST

EFFECTS OF SEA WATER AND CATHODIC PROTECTION ON CTOD FRACTURE TOUGHNESS OF TETHER ELEMENTS

Utført av/Work carried out by

Jens P. Tronskar, Hugo Ulle

Verifisert av/Work verified by

4 indekseringstermer (på engelsk)/4 indexing terms

- QUENCHED AND TEMPERED STEEL
- TETHER ELEMENTS
- FRACTURE TOUGHNESS
- CATHODIC PROTECTION

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27.9.1988	VT31	311086

Godkjent av/Approved by

Stig Wästberg

Stig Västberg
Head of Section

Klient, Oppdragsgiver/Client, Sponsor	Klient ref./Clients ref.	Rapporttype/Type of Report
Rautaruukki OY	D. Porter	Technical

Sammendrag/Summary

An experimental investigation has been conducted to assess the susceptibility o Saga, Grade I structural steel for developing local brittle regions in the heat affected zone of velds.

Testing vas performed on 25 and 50 mm Grade I steel plates supplied by Rautaruukki OY.

The results of the investigation shov that the Grade I steel from Rautaruukki OY has a lov susceptibility for local brittle zones for the specific conditions tested.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
88-3330	E3

Rapporttittel/Title of Report

ASSESSMENT OF SUSCEPTIBILITY OF SAGA GRADE I STRUCTURAL STEEL FOR LOCAL BRITTLE ZONES

Utført av/Work carried out by

K. Tronskar and H. Ulle

Verifisert av/Work verified by

4 indeksanngstermer (på engelsk)/4 index

- STEEL
- HEAT AFFECTED ZONE
- CTOD FRACTURE TOUGHNESS
- LOCAL BRITTLE ZONES

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Regionalkontorer/Regional Offices: BERGEN, STAVANGER

Dato/Date	Avd./Dept.	Prosjektnr./Project No.
7.10.1988	VT/31	311088

Godkjent av/Approved by

Stig Wästberg

Stig Västberg
Head of Section

Klient. Oppdragsgiver/Client. Sponsor	Klient ref./Clients ref.	Rapporttype/Type of Report
S.A. Fabrique de Fer de Charleroi	J.P. Gerard	Technical

Sammendrag/Summary

An experimental investigation has been conducted to assess the susceptibility of Saga, Grade I structural steel for developing local brittle regions in the heat affected zone of welds.

Testing was performed on 25 and 50 mm Grade I steel plates supplied by S.A. Fabrique de Fer de Charleroi.

The results of the investigation shov that the Grade I steel from Fabrique de Fer has a lov susceptibility for local brittle zones for the specific conditions tested.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
88-3333	E3

Rapporttittel/Title of Report

ASSESSMENT OF SUSCEPTIBILITY OF SAGA GRADE I STRUCTURAL STEEL FOR DEVELOPING LOCAL BRITTLE ZONES (LBZ)

Utført av/Work carried out by

J.P. Tronskar and H. Ulle

Verifisert av/Work verified by

G. WOLD

4 indekseringstermer (på engelsk)/4 indexing terms

STEEL
HEAT AFFECTED ZONE
CTOD FRACTURE TOUGHNESS
LOCAL BRITTLE ZONES

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Dato/Date	Avd./Dept	Prosjektnr. Project No
18 January 1988	VT31	311031

Godkjent av/Approved by

for Stig Wästberg
Head of Section

Klient. Oppdragsgiver/Client. Sponsor	Klient ref. Clients ref.	Rapporttype Type of Report
Norsk Hydro a.s	S. Roaas	Technical Report

Sammendrag/Summary

An investigation has been performed to study the HAZ CTOD fracture toughness of two 420 MPa minimum specified yield strength structural steels.

The steels were both controlled rolled and accelerated cooled with lov carbon content (0.07% wt) and Pcm 0.18.

One steel was a Ti O type and the other a Ti N type steel similar to the steel Oseberg grade I, used for the Oseberg project.

The results of the investigation shov that for the conditions tested the Ti O steel would be the best choice from the point of viev of grain coarsened and intercritical HAZ toughness.

VERITEC Rapportnr./Report No	Emnegruppe Subject Group
88-3029	E3

Rapporttittel/Title of Report

CTOD fracture toughness of 420 MPa yield strength structural steels - Brage development project.

Utført av/Work carried out by

Jens P. Tronskar, H. Ulle, A. Tjernæs

Verifisert av/Work verified by

G. Wold

Dato for siste revisjon Date of last rev.	Rev No	Antall sider Number of pages

4 indekseringstermer (på engelsk)/4 indexing terms

- CONTROLLED ROLLED
- ACCELERATED COOLED STEEL
- HEAT AFFECTED ZONE
- CTOD FRACTURE TOUGHNESS

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Dato/Date	Avd./Dept	Prosjektnr/Project No
28.01.1987	31	4203208

Godkjent av/Approved by

Stig Wästberg

Stig Wästberg
Head of Section

Klient/Oppdragsgiver/Client/Sponsor: Klient ref./Clients ref.

Esso, Norsk Hydro, Shell, SSAB
Statoil, Det norske Veritas

Rapporttype/Type of Report:

Technical

Sammendrag/Summary

Steel No. 1 (OX 602) has been studied with regard to susceptibility to temper embrittlement (TE). No effects of TE were found after a heat treatment cycle known to produce TE in susceptible steels.

VERITEC Rapportnr/Report No.	Emnegruppe/Subject Group
87-3058	E3

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH QT STEELS
IN OFFSHORE STRUCTURES

Activity 4.2 Temper embrittlement

Utført av/Work carried out by

G. Wold, T. Kristoffersen

Verifisert av/Work verified by

Dato for siste revisjon/ Date of last rev.	Rev.No.	Antall sider/

4 indeksenngstermer (på engelsk)/4 indexing term

- QT STEEL
- TEMPER EMBRITTLEMENT
- P-SEGREGATION
- MECHANICAL PROPERTIES

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Rapport/Report

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Dato/Date	Avd./Dept.	Prosjektnr./Project No.
06.02.87	31	4203208

Godkjent av/Approved by

Stig Wästberg

Stig Wästberg,
Head of Section, Strengths of Materials
and Structural Components

Klient, Oppdragsgiver/Client, Sponsor: Esso, Norsk Hydro, Shell, SSAB. Statoil, Det norske Veritas

Klient ref./Clients ref.:

Rapporttype/Type of Report: Technical

Sammendrag/Summary

The 50 mm plate material of steel No. 1 (OX 602) has been studied with regard to effects of hydrogen embrittlement. No such effects were found.

VERITEC Rapportnr./Report No.	Emnegruppe/Subject Group
87-3079	E3

Rapporttittel/Title of Report

EXPLOITING HIGH STRENGTH STEEL IN OFFSHORE STRUCTURES

Activity 4.3 Effects of Hydrogen

Utført av/Work carried out by: G. Wold G. Wold.

Verifisert av/Work verified by:

4 indeksenngstermer (på engelsk)/4 ind

QT-STEEL

HYDROGEN EMBRITTLEMENT

TENSILE TESTING

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